Structure of aluminum – zinc coated steel joints made by plasma arc brazing

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Keywords

Plasma arc brazing, zinc coated steel, aluminum, heterogenic joint, AlSi5, dissimilar materials

1. Introduction

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 aluminum to steel or zinc coated steel, melting temperature difference is almost 900°C (melting point of T(Fe) = 1535°C, T(Al) = 660°C). Joining of steel to aluminum (using non-pressure technology) is then characterized by the heterogenic joint; welded joint from the side of aluminum, brazed joint from the side of steel [1, 2]. 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 absence of volumetric defect and with required structure in the aluminum 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 [1 - 3]. Within the frame of arc technologies excepting the TIG and MIG welding, for the joining of zinc coated plates to aluminum, also the plasma arc process (PAW) is suitable, which is being often applied to the joining of zinc coated plates [4]. In the term of energy concentration level, plasma arc can be categorized right after the laser and electron beam [5, 6]. 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 [7].

At the metallurgical joining of dissimilar materials such as steel to aluminum, 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 Figure 1.

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.1), which consists of intermetallic phases of type Al_xFe_y. The nature of intermetallic phases (IM phases), their composition and thickness has an influence on the performed joint quality [8, 9]. The reason of IM formation consists in minimum dissolvability of Fe in Al in the solid state (Figure 2). These phases are having extremely high hardness values at ambient temperatures, up to 1200 HV and very low

Table 1. Selected physical and mechanical properties of Al and Fe [21].

Material	Tensile Strength (MPa)	Melting Temp. (°C)	Density ($kg.m^3$)	Specific Thermal Conductivity at 25°C ($kJ.m^{-1}.s^{-1}.K^{-1}$)
Fe	340¸470	1535	7850	0.46
Al 99,5	100	660	2700	2.09

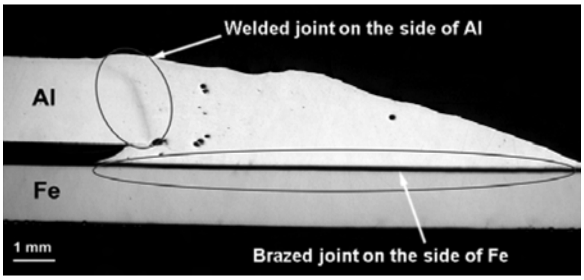


Figure 1. Al-Fe joints have a dual character; welded joint on the side of Al, brazed joints on the side of Fe.

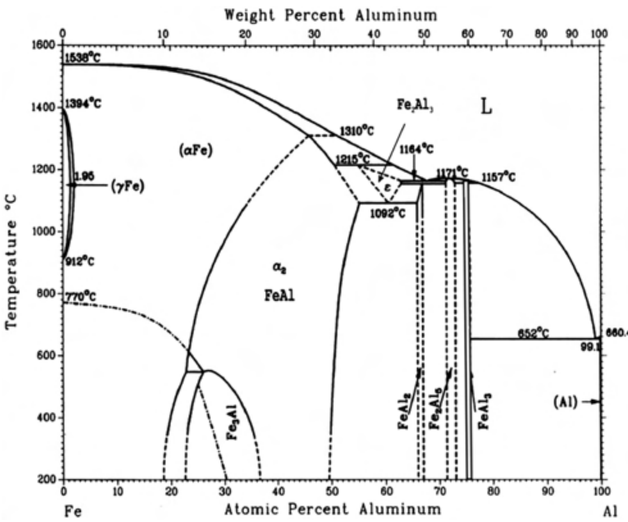


Figure 2. Fe – Al equilibrium phase diagram [13].

toughness [9, 10]. 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 the 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 [11, 12]. Ryabov [10] 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 aluminum to zinc coated plates, experiment has been carried out in two stages:

In the first stage, parameters of the production of overlapped joint samples have been optimized using 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.

In the second stage, samples performed with optimized parameters by plasma arc, have been analyzed 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 have been used:

- Cold rolled plate, zinc coated on both sides, type DX53+Z 100MB, plate thickness 1.5mm (designation according to STN EN 10142), thickness of zinc layer 6 ÷ 12 μm [14].
- Al99,95 aluminum plate, thickness 2 mm.
- Filler material, AlSi5 wire (ESAB OK AUTROD 4043), designation according to EN ISO 18273: S Al 4043 (AlSi5); diameter 1.0 mm [22].

Procedure of sample joints production has been as follows:

1. Samples of dimensions 150x50 mm^2 have been cut from the blank plate material.
2. Aluminum plates have been mechanically brushed and cleaned prior to welding using the stainless steel brush and an acetone.
3. Plates have been positioned to constant overlapped joint position and fixed by spot welds. Joint positioning scheme is displayed in Figure 3.

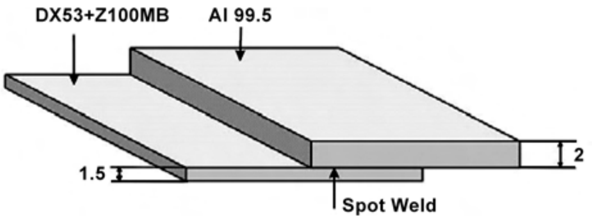


Figure 3. Positioning of plates for the welding/brazing.

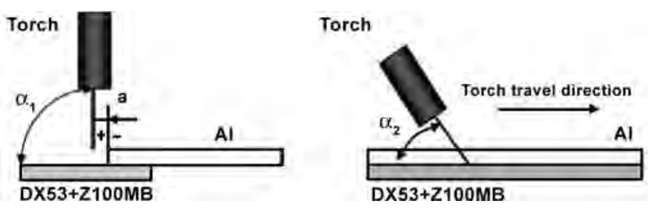


Figure 4. Torch positioning and movement scheme: α_1 – angle of torch in the perpendicular direction to the axis of joint, α_2 – angle of torch in the parallel direction to the axis of joint, a – distance between the torch nozzle axis and the axis of Al plate edge.

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 is displayed in the Figure 4.

The heat input per the length unit produced by plasma arc welding/brazing process has been calculated according to the following formula [15].

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

where:

k - Coefficient of thermal efficiency of welding method, k (PAW) = 0.6 [24],
U - Voltage [V],
I - Amperage [A],
v_s - Welding speed [mm.s^{-1}].

Sample joints have been performed 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 plasma arc welding/brazing process of zinc coated plates to aluminum has been carried out using the parameters given in Table 2.

Table 2. Plasma arc welding/brazing process parameters.

Process parameter	Value
Plasma current I_P (A)	40 ÷ 80
Voltage on arc U_P (V)	15 ÷ 18
Welding speed: v_s (mm.s^{-1})	3.3 ÷ 5.0
Wire feed speed: v_F (m.min^{-1})	2.16 ÷ 3.04
Torch movement geometry (see fig.5)	α_1 = 75 ÷ 90°, α_2 = 75°, a = 0 ÷ + 4.5 mm
Wire diameter ∅ (mm)	1.0
Heat input Q (kJ.mm^{-1})	108.1 ÷ 172.9x10^{-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

Results

In the optimization process of 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 (Figure 5).

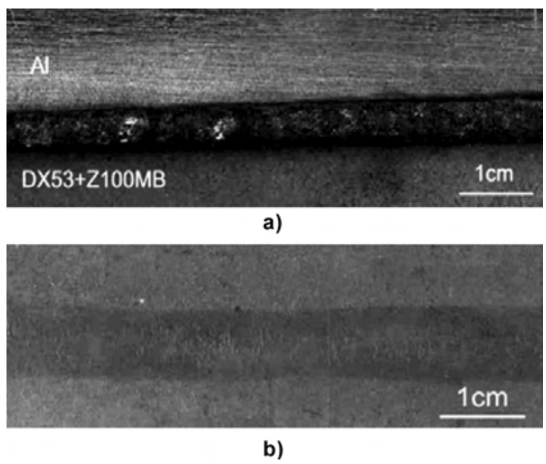


Figure 5. Plasma Arc welded/brazed joint in the protection of Ar, Q =144.12x10^{-3} kJ.mm^{-1}: a) joint surface b) bottom side of the joint.

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 the following parameters:

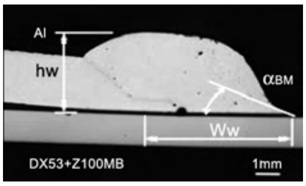
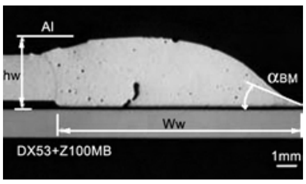
- width of the contact area from the side of zinc coated plate,
- wetting angle from the side of the zinc coated plate,
- porosity of the weld metal.

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 has shown the following findings:

A. Amount of heat input affects the geometry of the joint. Measurements of the contact area (weld) width w_W and wetting angle a_{BM} on the selected sample joints has shown that increasing of the heat input results in the increase of the contact area. The highest width values (w_W = 11.5 ÷ 13.7 mm) have been measured at the heat input Q = 162.2x10^{-3} kJ.mm^{-1} on the sample performed by plasma arc process in He. The values of wetting angle on the samples performed by plasma arc have been measured in the range of α_{BM}= 14 ÷ 41°. According to this measured values, the wettability can be classified as ”very good“ up to “excellent”. Cross sections of selected joint samples performed using plasma arc process are documented in Table 3.

Table 3. Cross sections of selected joints performed by Plasma arc process with the optimized parameters.

Cross Sections	w_W	h_W	α_{BM}	Porosity
	(mm)		(º)	(%)
 Plasma Arc in the protection of Ar, Q .10^{-3} = 144.1(kJ.mm^{-1})	7.5	3.8	18	0.6
 Plasma Arc in the protection of He Q .10^{-3} = 162.2(kJ.mm^{-1})	12	3.6	19	0.78

Joint samples, which have been performed with optimized parameters, have been further subjected to:

- Microscopic analysis, where the thickness interface layer has been measured from the side of brazed joint.
- EDX analysis, in order to identify the composition of elements presented in the interface layer and to determine the phase composition.

Based on the existing literature sources [10, 16], 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 plasma arc process in four locations (I, II, III, IV) of reaction zone according to the scheme in Figure 6. In each location, three measurements have been performed. Figure 7 and 8 documents the measuring of the transition zone thickness; (measuring location II, fig. 6); average measured values of transition zone thickness are included in Table 4.

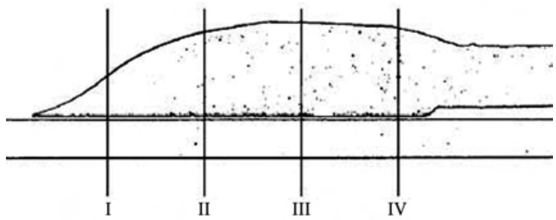


Figure 6. Scheme of interface layer thickness measuring.

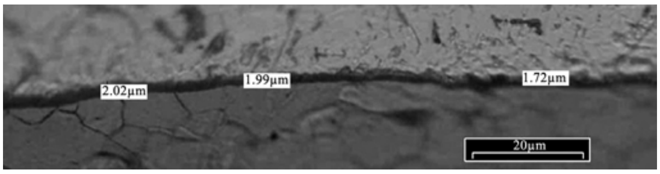


Figure 7. Interface layer of the joint performed by plasma arc process in Ar.

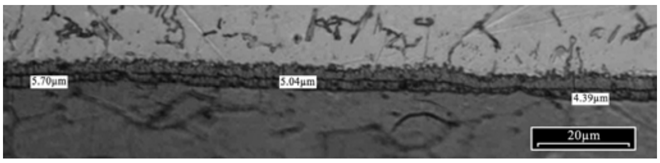


Figure 8. Interface layer of the joint performed by plasma arc process in He

Measurement results of interface layer thickness (tab. 4) and interface layer shape (fig. 7 and 8) have shown that interface layer thickness has different values and varies depending on shielding gas and the location of measurement. Comparing the joint samples performed 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 [17]. Thermal output

Table 4. Average values of the transition zone thickness of joints.

Process	Average value of the interface layer thickness (μm)
Plasma Ar	1.9
Plasma He	5.5

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 [10], 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 measurement have shown that the value of 10 µm has not been exceeded in either case. Analysis of the interface layer thickness has shown that 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 has been identified the most uniformly and sharply defined interface layer with the lowest thickness values ranging from 1.46 to 2.21 µm.

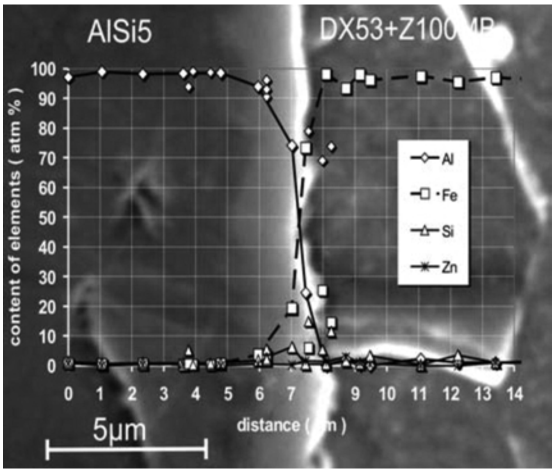


Figure 9. Concentration profiles of the AlSi5-DX53+Z100MB interface layer; sample performed by plasma arc process in the protection of Ar.

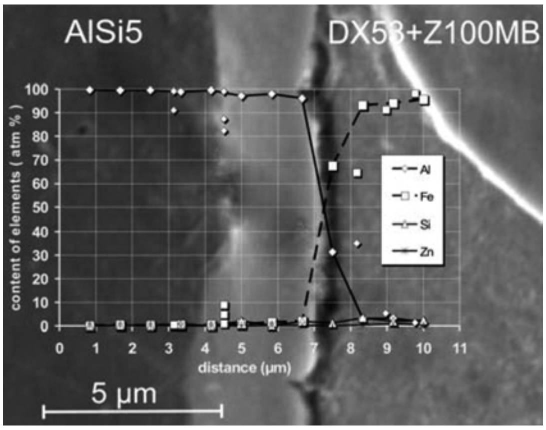


Figure 10. Concentration profiles of the AlSi5-DX53+Z100MB interface layer; sample performed by plasma arc process in the protection of He.

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 has been evaluated using the electron microscope JEOL JSM 5310, which has been equipped by the energy-dispersive x-ray spectrometer KEVEX delta IV. Atomic and mass determination of elements has been evaluated using the EDX analysis perpendicular to the interface of zinc coated steel plate – AlSi5 weld metal (Figure 9 and 10).

Measured values have been processed to the diagrams showing the progression of atomic and mass concentration of Al, Fe, Si and Zn in the dependence on the distance from the interface layer. The structure has been specified on the base of EDX analysis results, Al-Fe and Al-Si phase diagrams, Al-Fe-Si ternary system and literature sources [13, 19, 20].

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 has been found a higher content of Fe, while its increase in the interface layer corresponded to the decrease of Al content. EDX analysis results have shown intensive diffusion of Si to the interface layer, while its maximum content has reached the value of 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

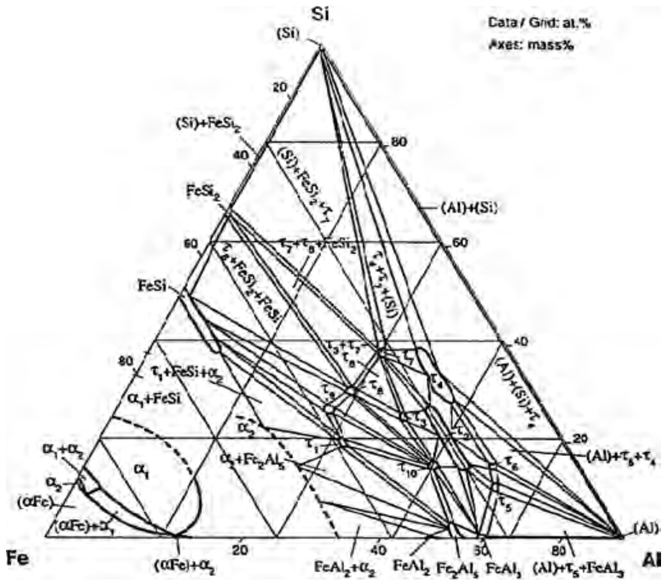


Figure 11. Isothermal section of the Al–Fe–Si system at 600°C [20].

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 aFe, intermetallic phases $FeAl_2$, $FeAl_3$ (fig. 2) and ternary phases of type τ_5 ($Al_{15}Fe_6Si_5$); τ_6 ($Al_{4,5}FeSi$). (Figure 11)

Conclusion

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 aluminum using the AlSi5 wire. For the purpose of comparison, overlapped sample joints have been performed with optimized parameters by plasma arc process. Parameters have been optimized on the base of the visual examination; evaluation has been supplemented by macroscopic analysis of joints in cross sections. In the next part, joint samples performed with optimized parameters have been 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 (see tab. 3).

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 [18]. 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 (see tab. 3).

2. During the microscopic analysis of joint samples, attention was focused on the evaluation of thickness and structure analysis of interface layer between zinc coated plate and AlSi5 weld metal which are decisive in the term of the mechanical properties of joint (presence of intermetallic phases). The evaluation of thickness and character of interface layer has shown, that the mentioned criteria depends on the parameters of the process. Structure and thickness of transition zone was significantly affected by the process thermal cycle, which has an influence on the processes of diffusion, what was also reflected in the thickness of interface layer measured in different locations of the joint (see tab.4). The minimum average thicknesses has been measured on joint samples prepared by plasma arc process in the protection of Ar, average and maximum thickness has been 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 [9, 10], which states, that the highest strength of a joint can be reached on the condition that transition zone doesn't 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.

3. The results of EDX analysis have shown the intense diffusion of Si to the transition zone where the highest measured value was 14.9 atm % Si. As expected, the diffusion of Fe to the transition zone has been 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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