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STRUCTURAL AND MECHANICAL PROPERTIES OF BRAZED JOINTS OF STAINLESS STEEL AND ALUMINIUM

WŁASNOŚCI STRUKTURALNE I MECHANICZNE TWARDO LUTOWANYCH POŁĄCZEŃ STALI NIERDZEWNEJ Z ALUMINIUM

Development of metals and alloys joining technology in modern scopes of industry is largely related to research of new technology of joining the materials of different physical and chemical properties.

It deals with joining of stainless steel with lights metals as aluminum and its alloys. Obtaining the good quality and the high strength joints of this type is actually important technological and research problem. These properties are largely dependant of the appearance of brittle intermetallics in form of layers.

Brazing is one of fundamental methods of performing these joints.

In this publication the brazeability of composition stainless steel – aluminum is characterized and previous research attainment in the scope of brazing of this composition is discussed.

There are also presented the results of investigation carried out in Institute of Welding in Gliwice. These investigations were conducted using the method of brazing with different rate of heating e.g. induction brazing in air (quick) and furnace brazing in argon atmosphere (slow).

The filler metals of near eutectic composition Al-Si without alloying elements and with Ni and Cu were used.

For all brazing joints the results of shear strength depended on holding time in brazing temperature and the results of structure analysis with kinetic of formation brittle phases are presented. The obtain results of investigation made it possible to select the best technological conditions of brazing of stainless steel and aluminum.

Keywords: brazing, furnace brazing, induction brazing, stainless steel, aluminum, intermetallics phases, mechanical properties of brazed joints, brazing parameters

Rozwój technologii łączenia metali i stopów w nowoczesnych dziedzinach przemysłu wiąże się w dużej mierze z opracowywaniem technologii łączenia materiałów o zróżnicowanych własnościach fizycznych i chemicznych. Dotyczy to między innymi łączenia stali nierdzewnej z metalami lekkimi np. z aluminium i jego stopami. Uzyskanie połączeń tego typ o dobrej jakości oraz o wysokich własnościach mechanicznych stanowi aktualnie ważny problem technologiczny i badawczy. Własności te są w znaczącym stopniu uwarunkowane występowaniem warstwowych wydzieleń kruchych faz międzymetalicznych w połączeniach.

Do podstawowych metod wykonywania ww. połączeń należy lutowanie twarde. W artykule scharakteryzowano lutowalność układu materiałowego stal nierdzewna – aluminium oraz omówiono dotychczasowe osiągnięcia badawcze z zakresu jego lutowania.

Przedstawiono również własne wyniki badań, realizowanych w Instytucie Spawalnictwa w Gliwicach. Badania te prowadzono przy zastosowaniu do lutowania nagrzewania o zróżnicowanej prędkości – indukcyjnego (szybkie) na powietrzu i piecowego (wolniejsze) w atmosferze argonu. Jako luty stosowano stopy Al-Si o składzie zbliżonym do eutektycznego bez dodatków stopowych oraz z dodatkiem Ni i Cu. Dla wszystkich połączeń lutowanych przedstawiono wyniki wyniki metalograficznej analizy strukturalnej z uwzględnieniem kinetyki powstawania kruchych i twardych faz oraz badań wytrzymałości na ścinanie w zależności od czasu wytrzymania próbek w temperaturze lutowania. Uzyskane wyniki badań pozwoliły na dobór najkorzystniejszych warunków technologicznych lutowania twardego stali nierdzewnej z aluminium.

1. Introduction

The development of technologies used for joining metals and alloys in modern sectors of industry and economy is strictly connected with a necessity to join materials of varied physical and chemical properties. The aforesaid types of connections include joints of highly alloyed stainless steels with light metals such as aluminium or titanium or their alloys. It should also be mentioned that the above metals and alloys form the base for modern metal-based composites used as the so-called "advanced materials" in critical joined structures. Therefore,

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joining of steels with light metals by means of welding techniques (welding, pressure welding, brazing) constitutes currently a research and technological problem of great importance. The above joints are quite frequently characterised by relatively poor mechanical properties due to a content of hard and brittle inter-metallic phases present in the form of continuous layers in the boundary areas of joints [1,2,16,17].

Nowadays, the most commonly applied methods of joining stainless steels with aluminium and its alloys include tungsten inert gas (TIG) welding and metal inert gas (MIG) welding, welding with concentrated energy beam (electron and laser), friction welding, explosive welding, diffusion welding as well as MIG braze welding and brazing [3÷11]. The application of the above joining methods depends on the structural form of joined elements, joint-related operational requirements as well as economics of joining processes.

Due to a relatively low process temperature, not exceeding 600÷620°C, as well as a possibility to make all joints in complex structures during one process cycle, brazing is commonly applied in joining of thin-walled elements or components having complex structure and a significant number of joints. For instance, brazing is used in the production of aviation accessories, cryogenic equipment, heat exchangers, chemical plants as well as elements of household goods.

This publication presents the results of investigation of the impact of material and technological conditions of brazing stainless steel with aluminium on mechanical properties of joints determined by the occurrence of brittle inter-metallic phases. The aforesaid research has enabled the development of the most favourable conditions of furnace brazing in chemically inert atmosphere as well as of induction brazing in air atmosphere [18].

2. Brazability of composition: stainless steel – aluminium

While discussing the brazability of the composition: stainless steel (type 18-8) – aluminium and its alloys, it should be emphasized that these materials considerably differ as regards their physical and chemical properties such as density, melting point, heat expansion and conductivity, hardness, tensile strength as well as stability of oxides present on their surface. Therefore, in the aforesaid material composition it is technologically difficult to obtain brazed joints of good quality and required operational characteristics (mechanical strength, leakproofness, corrosion resistance). The foregoing is determined by poor wettability of both materials when treated with Al-Si-based braze alloys; this being caused by the presence of high-melting superficial layers formed from stable oxides (Al_2O_3; FeO-Cr_2O_3, sometimes also TiO_2 and NbO) as well as due to the formation of layers of brittle inter-metallic phases (especially Fe-Al type) in the joint area. In addition, different heat expansion and conductivity of the materials favours stress formation and cracking of joints [1÷11].

Notwithstanding the foregoing, in previous publications on brazing of (non-alloyed and stainless) steels with aluminium, the aforesaid joining method is considered superior to inert gas arc welding, mainly due to a lower process temperature and related limited formation of brittle inter-metallic phases in the joint [2, 7÷11].

It was also observed that, at brazing temperature the silicon contained in Al-Si type fillers effectively slows the kinetics of the formation of the hardest Fe-Al type phases (especially Fe_2Al_5 type phases) in the joint [7, 12] and facilitates the formation of complex Fe-Al-Si type phases of lower hardness as first.

Available specialist scientific and technical publications on the subject, however, do not provide any in-depth information about brazing technology and properties of brazed joints. Very few publications refer to specialised application-related examples and the most convenient temperature and time parameters for the aforesaid processes allowing for the highest strength of brazed joints differ quite significantly. More information about the formation and kinetics of the growth of inter-metallic phases in the stainless steel-aluminium composition may be found in publications concerning aluminium composites with steel fibre reinforcement [13÷15]. The usefulness of such information for interpretation of changes which occur during brazing of the aforementioned materials remains very limited as in most of the cases it refers to the impact exerted in solid state, whereas in brazing processes, aluminium filler material is liquid.

3. Investigation and results

Parent and filler metals

The investigation involved the application of the following parent metals:

- aluminium – rod: grade EN-AW1050A (Al 99.5) according to PN-EN 573-3:1998;
- stainless steel – rod: grade X10CrNi18-8 according to PN-EN 10088-1:1998 (chemical composition according to analysis: 0.063 %C; 17.66 % Cr; 8.29% Ni; 0.18% Si; 2.07% Mn).

From among the publication-recommended silumin braze alloys, the filler material selected for making joints of stainless steel and aluminium was the AlSi12 braze alloy (of nominal composition close to eutectic) as well as two other braze alloys with similar silicon content (approx. 12%) with addition of, accordingly, Ni and Ni-Cu. Braze alloys with Ni and Ni-Cu are characterised by a slightly lower melting point and better strength properties than silumin void of the aforesaid alloy additions [2, 9]. It was also assumed that due to Ni and Cu content, the braze alloys should wet stainless steel better and be characterised by more convenient chemical and diffusive impact on the interphase border with steel because of the possibility to form more complex intermetallic phases not as hard as Fe-Al type phases.

The nominal compositions and melting points of the selected testing braze alloys are presented in Table 1. Apart from (Lincoln-manufactured) AlSi12 braze alloy, the aforesaid braze alloys were smelted from chemically pure ingredients under fluoride-chloride flux in a graphite melting pot; the ingredients were induction heated with a machine generator (type UFW-28/8; manufactured by Germany's VFW). The braze alloys were shaped as rods of 3-mm diameter and 300-400mm in length; the rods were prepared by sucking liquid alloys from the melting pot through quartz pipes.

TABLE 1

Aluminium filler metals used in tests

No.	Filler metal designation	Melting point °C	Chemical composition, %, m/m (Al remainder)			
			assumed		according to chemical analysis	
			Si	others	Si	others
1	AlSi12	577-582	12	–	11.67	–
2	AlSi12Ni	569-580	11.7	44.5 Ni	12.01	4.82 Ni
3	AlSi12NiCu	553-580	12	4.1 Ni	11.79	4.04 Ni
				2.7 Cu		2.87 Cu

Preparation of test specimens

The specimens of joints brazed with the aforementioned braze alloys combined with non-corrosive fluoroaluminate flux Nocolok (manufactured by Solvay) designated for structural tests and shear strength tests were made as butt joints of cylindrical elements (rollers) of the following dimensions: aluminium roller – Ø 30x15mm; steel roller – Ø 15x15mm. In order to provide the elements with a required brazing gap, it was necessary to apply spacers made of tungsten wire (0.2mm in diameter). Two methods of various heating rates were selected to heat testing joints so that they could reach an appropriate brazing temperature. One of the methods was slower furnace heating in argon atmosphere under pressure reduced to 3.4 kPa. The specimen was heated in a TORVAC-model S 16 vacuum furnace. The other method consisted in quick induction heating of a specimen with an induction inverter generator (NG-15 type) in air atmosphere. The inverted generator used for heating had been manufactured at the Instytut Spawalnictwa in Gliwice and was equipped with a cylindrical three-coil heating inductor.

The joints were brazed at a temperature of 605±5°C measured on the specimens. During the furnace brazing, hold times amounted to 5, 10, 15, 20 and 40 min accordingly, and were measured after the specimen had reached a temperature of 600°C (the heating time was approx. 20 min). During induction brazing, a joint was held at a temperature of 605±5°C for approx. 2÷3s. Longer holding of the joined elements at the brazing temperature resulted in intense dissolving of aluminium elements in the liquid braze alloy.

After visual inspection, the joined specimens were machine worked in order to prepare cylindrical specimens of nominal diameter of 15mm and length of approx. 20mm.

Structural analysis of brazed joints

The examination of joints of X10CrNi18-8 stainless steel with EN-AW1050A aluminium brazed with three testing brazes i.e. AlSi12, AlSi12Ni and AlSi12NiCu involved observation of the structures of joints by means of a Leica-made MEF4M optical microscope as well as a scanning electron microscope. The investigation also included a local qualitative and quantitative analysis of phases. The latter type of examination was conducted at the Laboratory of Electron Microscopy of the Institute of Non-ferrous Metals in Gliwice and involved the application of an X-ray JEOL-manufactured microprobe analyser (JCXA 7333) equipped with an energy-dispersion spectrometer (EDS) (model LINK ISIS made by Oxford Instruments).

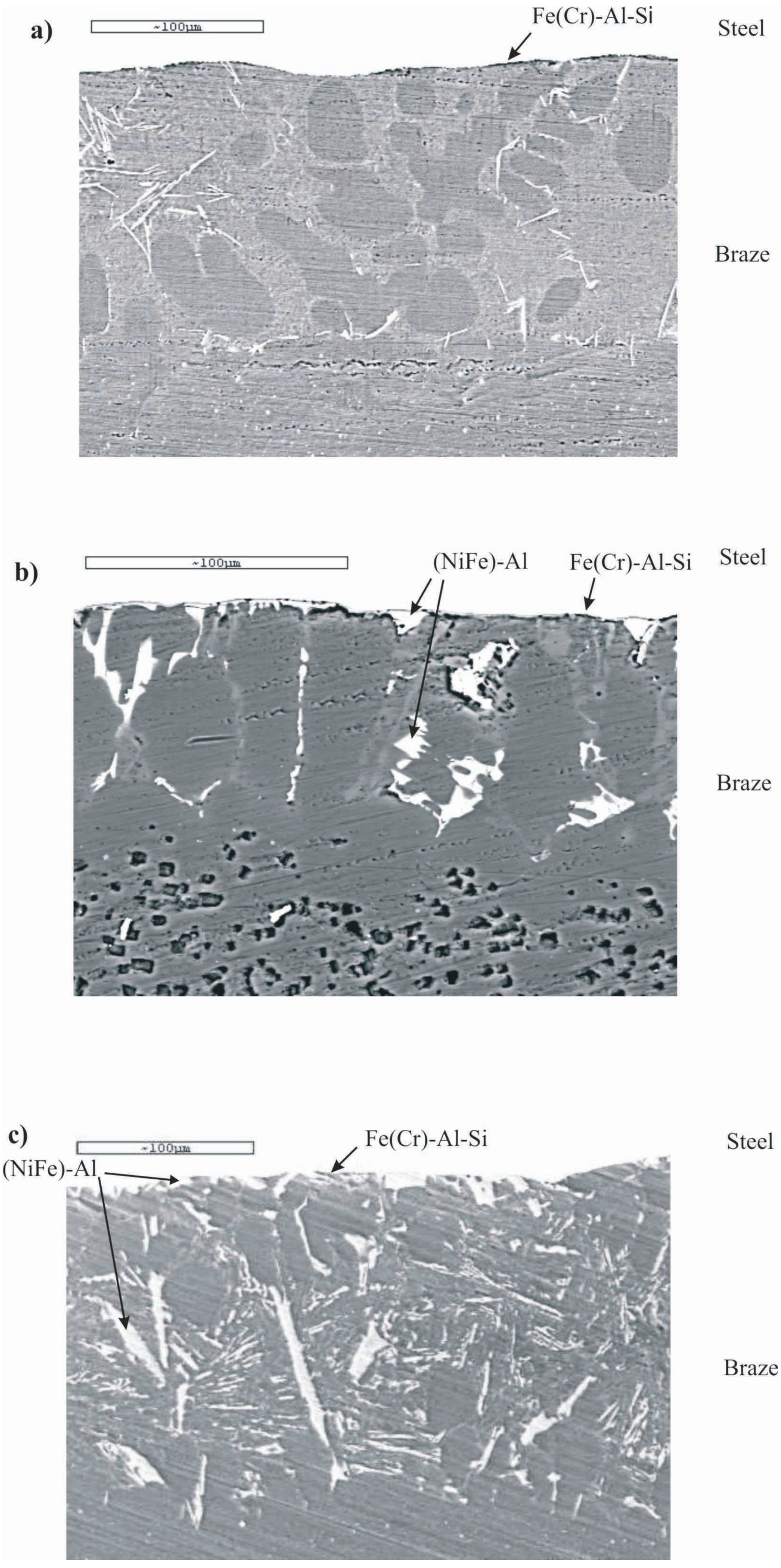

Fig. 1. Structure of interphase boundary of brazing seam and steel in steel X10CrNi 18-8 – aluminium EN AW1050A, induction brazed

The structures of the above joints were also subject to selective diffraction examination with a JEOL-made 100B transmission electron microscope. The examination was conducted at the Chair of Materials Science of the Faculty of Materials Technology and Metallurgy at the Silesian University of Technology in Katowice.

The metallographic examination of the structures of the aforesaid joints revealed the presence of layer formations on the side of the steel. The formations in question were decisive for strength properties of the joints as it was in this particular place where specimens were separated during shearing of the joints. In order to identify the phases more precisely, the above fragments were subject to micro-radiographic analysis as well as electron diffraction analysis.

The structural examination of the joints of stainless steel with aluminium revealed that the formation of layer brittle phases on the border of the brazes with the steel was very similar in case of all testing brazes applied (AlSi12, AlSi12Ni and AlSi12NiCu). At relatively short hold times (3 s ÷ 5 min) at which the joined elements were exposed to brazing temperature (during induction and furnace brazing), it was possible to observe initial formation of a thin (1÷2μm) and discontinuous layer of Fe (Cr) - Al - Si type phase of the following chemical composition (% at.): 69.54÷73.63% Al 10.56÷13.46 % Fe, 9.73÷11.49 % Si, 4.07÷5.56 % Cr, 0.21÷0.88 % Ni and, additionally, 0.72÷1.42 % Cu in the joint made with AlSi12NiCu braze (Fig. 4). An increase in hold time up to 10-15min resulted in thickening of the aforesaid layer up to approx. 22÷27μm (Fig.2a,3a,4a). The cross-section of the layer revealed slight fluctuations of chemical composition i.e. increasing Al content and decreasing Fe content towards the braze. The diffraction analysis enabled identification of the $FeSi_2Al_3$ intermetallic phase as the base of the layer (Fig. 5). In the structures of all of the above joints made with hold times of 15min and longer, it was possible to observe the formation of another, initially discontinuous, layer of Fe(Cr) – Al type phase on the side of the steel. The chemical composition range of the layer was as follows (% at.): 63.26÷67.34 % Al., 18.09÷21.68 % Fe, 5.56÷9.05 % Cr, 2.58÷4.56 % Si, 1.88÷3.89 % Ni (Fig. 2b, 3b, 4b). The above layer had a complex structure; the diffraction analysis revealed that the layer base was the $FeAl_3$ intermetallic phase (Fig. 5). The thickness of the layer after hold time of more than 20min exceeded 4μm and after 40min – reached approx. 9μm. The thickness of the $FeSi_2Al_3$ phase-based layer amounted to 45 and 50 μm accordingly (Fig. 2b, 4b, 6b). At the same time, the examination of the joints made with AlSi12Ni and AlSi12NiCu braze alloys at hold times over 10min. revealed that on the brazed joint side there was the (NiFe)-Al type phase with the following chemical composition range (% at.): 77.23÷80.50 % Al, 8.43÷8.77 % Fe, 9.81÷13,37 % Ni, 2.29÷2.45 % Si, 0.17÷0.43 % Cr (Fig. 3, 4). The determination of the base of the aforesaid complex layer requires further analytical examination. It should be emphasized that the above layer formations were present in the whole volume of joints made with AlSi12Ni and AlSi12NiCu braze alloys and tended to concentrate on the border of the joint with the steel. The total thickness of the layers based on $FeSi_2Al_3$ and (NiFe)-Al phases in the joints made with silumin brazes with nickel only and nickel and copper, exposed to brazing temperature at hold times exceeding 20 min corresponded to the thickness of the layer of the $FeSi_2Al_3$ phase in the joints made with the AlSi12 braze alloy (Fig. 2b, 3b, 4b).

The structure of layers of all of the above phases revealed the presence of numerous longitudinal and transverse cracks and delaminations whose size and number increased with the brazing time. This, in turn, reveals their high brittleness and hardness, confirmed later by results of micro-hardness tests (average result of 3 measurements):

$FeAl_3$	641 HV 0.05
$FeSi_2Al_3$	514 HV 0.05
(NiFe) – Al	260 HV 0.05

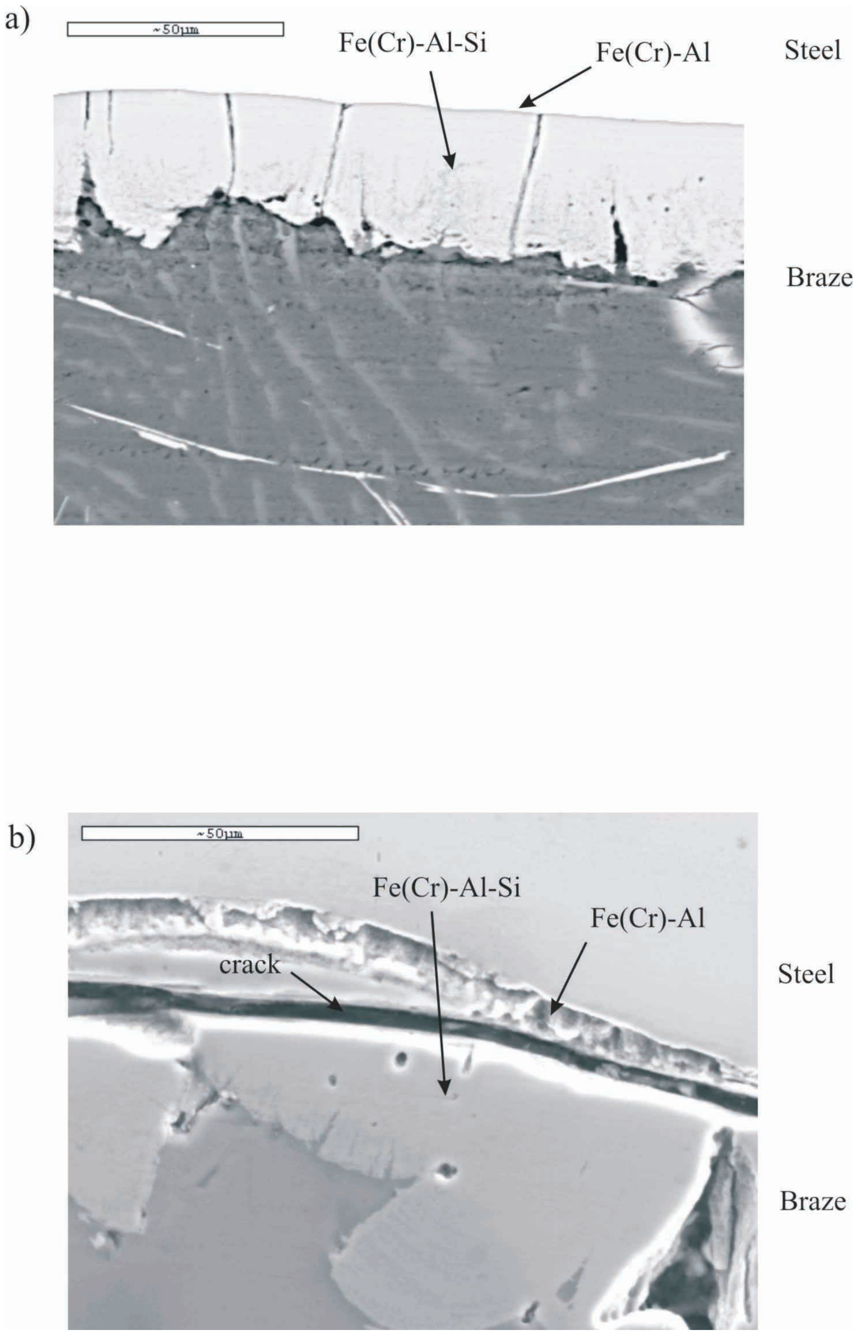

Fig. 2. Structure of interphase boundary of brazing seam and steel in steel X10CrNi 18-8 – aluminium EN-AW1050A furnace brazed joints in argon atmosphere with filler metal AlSi12; brazing temperature and time: 605 °C /15min (a), 605 °C /45min (b), (ESM-comp.)

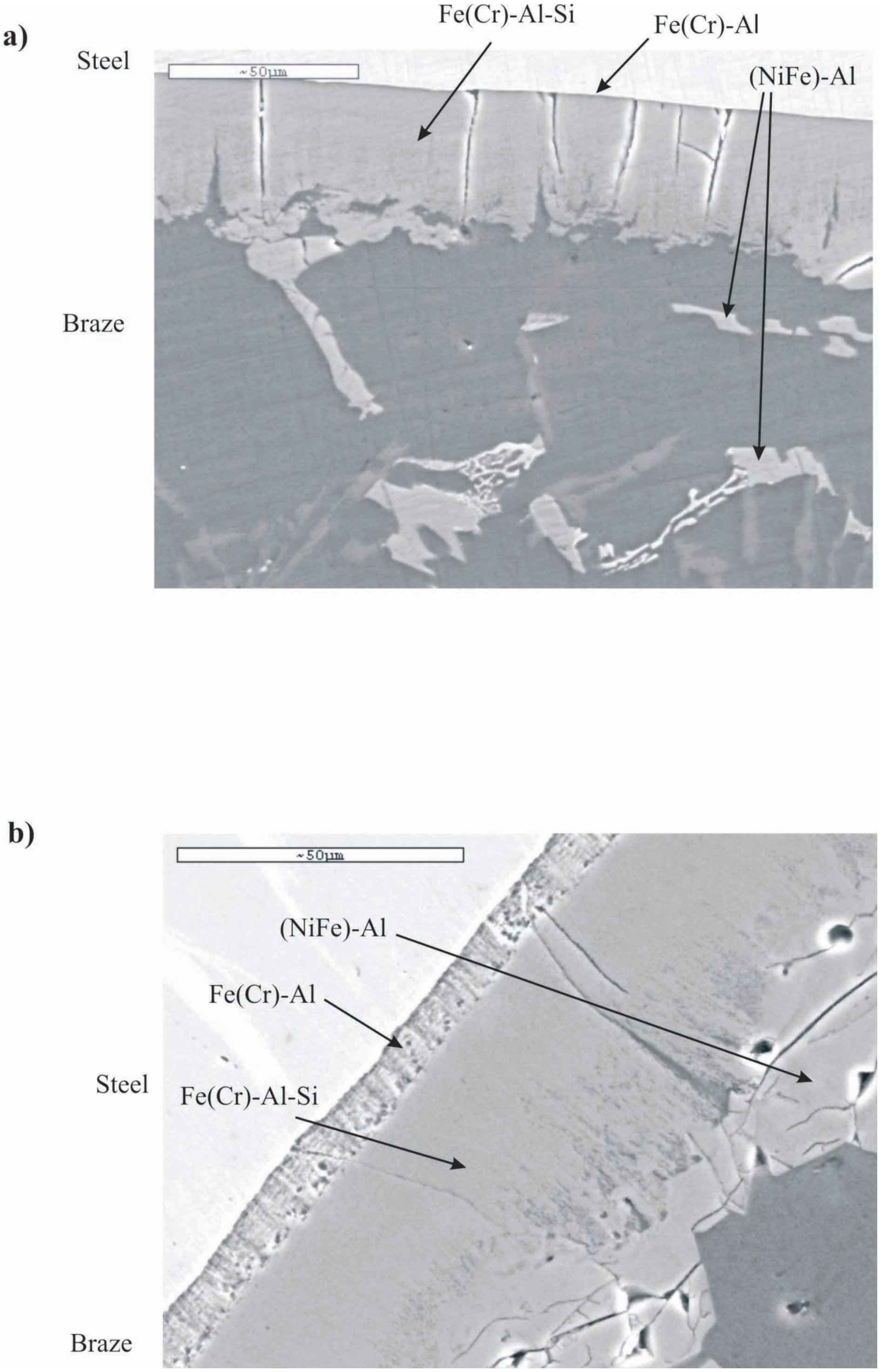

Fig. 3. Structure of interphase boundary of brazing seam and steel in steel X10CrNi 18-8 – aluminium EN-AW1050A furnace brazed joints in argon atmosphere with filler metal AlSi12Ni; brazing temperature and time: 605 °C /15min (a), 605 °C /45min (b), (ESM-comp.)

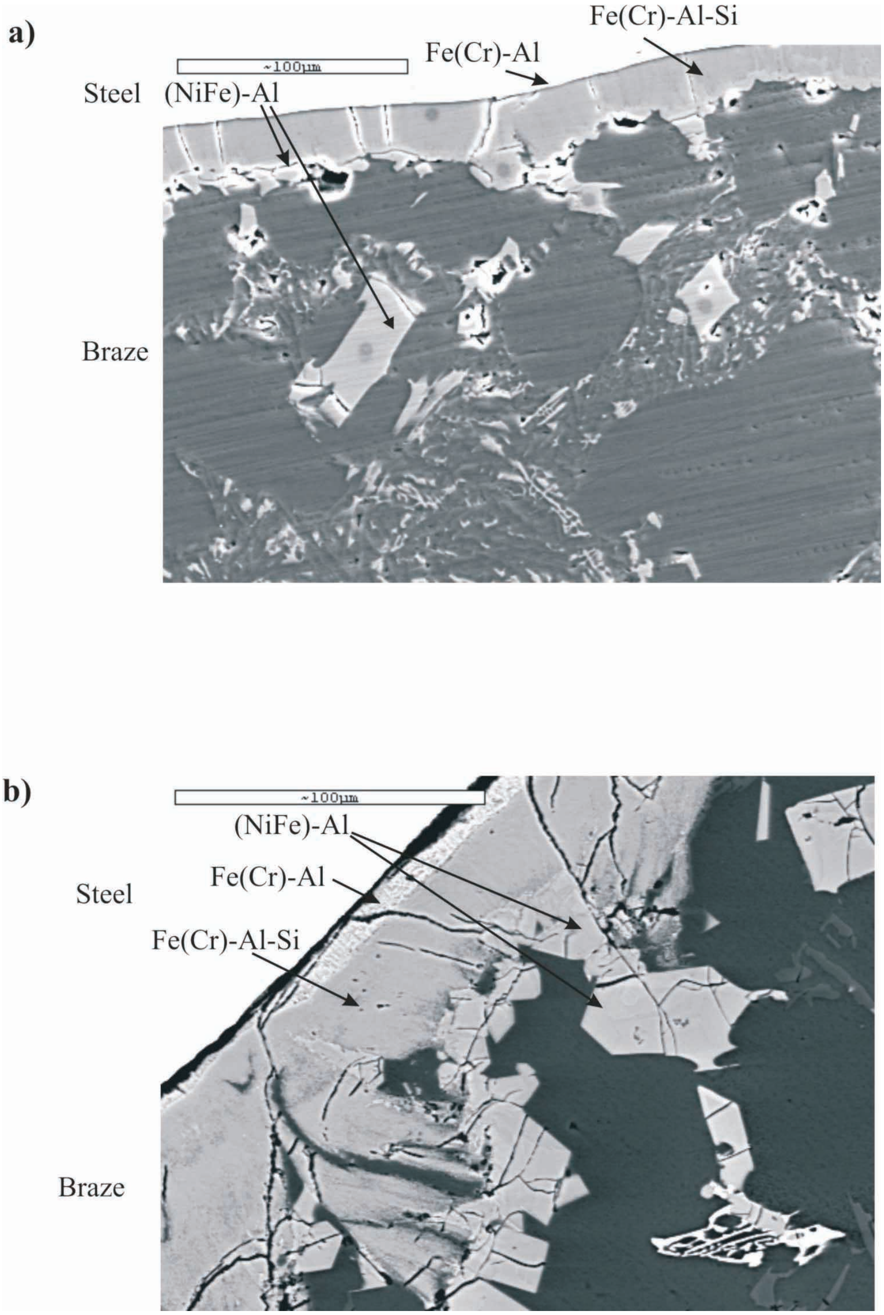

Fig. 4. Structure of interphase boundary of brazing seam and steel in steel X10CrNi 18-8 – aluminium EN-AW1050A furnace brazed joints in argon atmosphere with filler metal AlSi12NiCu; brazing temperature and time: 605 °C /15min (a), 605 °C /45min (b), (ESM-comp.)

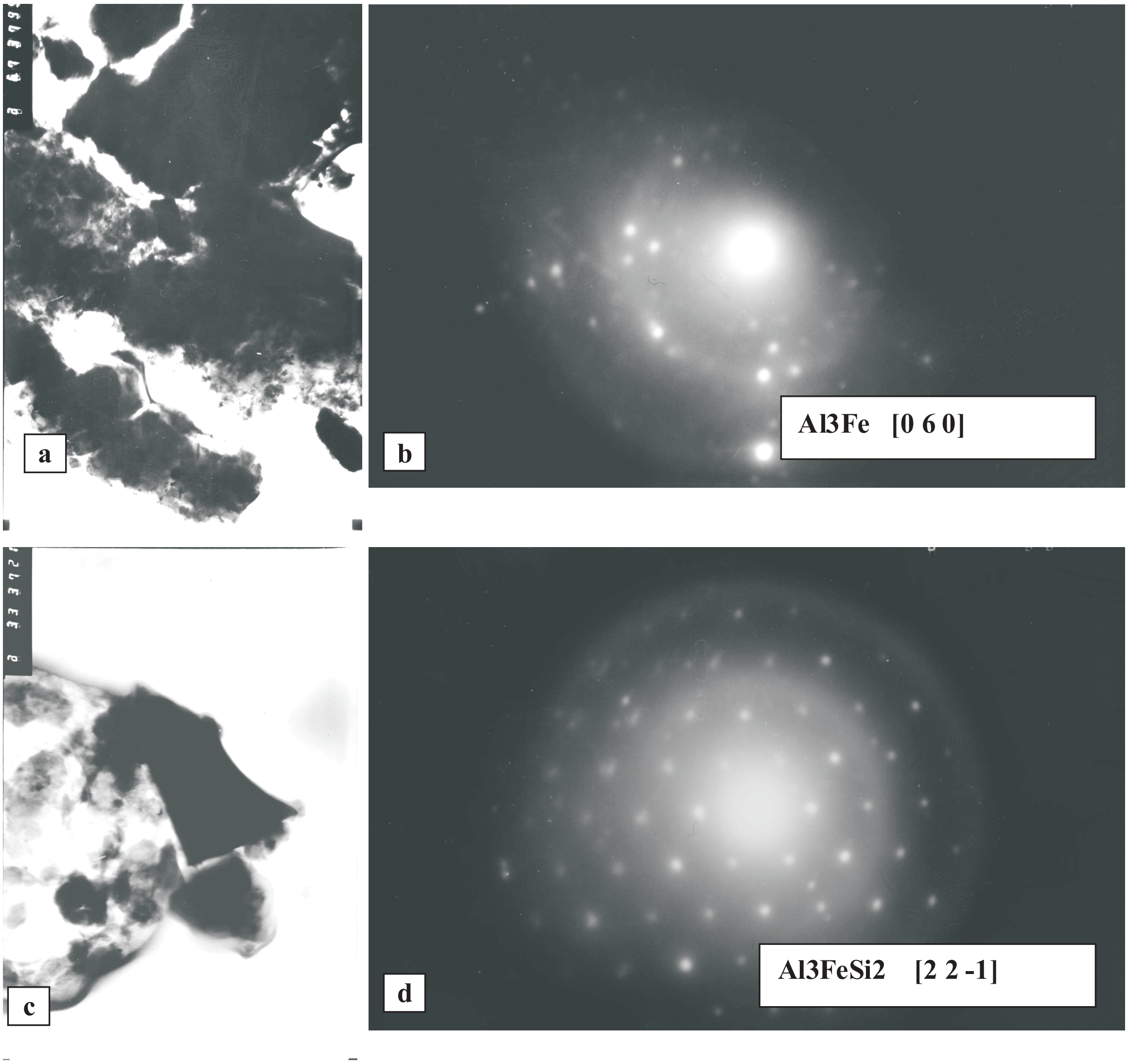

Fig. 5. Diffraction patterns (electrograms) of the phases on the border: stainless steel – brazed joint in the joints of the X10CrNi 18-8 stainless steel with the EN-AW1050A aluminium by means of Al-Si braze alloy

Shear strength of brazed joints

The cylindrical specimens of brazed joints of stainless steel and aluminium were subject to crosswise shearing (in the brazed joint) by means of special auxiliary equipment. The specimens were sheared with an Instron-manufactured testing machine (model 4210). The results of the examination are presented in Tables 2 and 3.

In case of furnace brazed joints, the results of tests revealed a decrease in shear strength values related to increasing hold time of specimens exposed to brazing temperature (Table 3). In case of all braze alloys (AlSi12, AlSi12Ni AlSi12NiCu) it was possible to observe that a more evident decrease in strength occurred at hold times exceeding 15min. This phenomenon remains in strict connection with the formation of a solid solution layer based on a very brittle FeAl3 phase. The shear strength of joints made with brazes containing nickel and nickel with copper, exposed to brazing temperature at shorter hold times (5÷15 min) was lower than the strength of the joints made with silumin brazes containing no alloy additions. However, induction brazed joints (hold time at brazing temperature of 2÷3 s) revealed slightly higher shear strength in case of all brazes if compared with furnace brazed joints (Table 4). They also revealed the presence of the thinnest layers of brittle phases on the border of the brazed joint and the steel.

TABLE 2

Shear strength of joints: stainless steel (X10CrNi18-8) – aluminium (EN-AW1050A) furnace brazed in argon atmosphere with the use of fluoroaluminate flux

No.	Filler metal	Brazing time1) min.	Shear strength2) MPa		
			x	Sx	PU
1	AlSi12	5	22.65	2.43	19.4 ÷ 25.89
2		10	22.19	2.19	19.15 ÷ 25.23
3		15	21.68	2.52	18.18 ÷ 25.18
4		20	20.16	1.45	18.14 ÷ 22.18
5		40	18.31	2.23	15.22 ÷ 21.40
6	AlSi12Ni	5	28.01	2.55	24.47 ÷ 31.55
7		10	27.95	2.59	24.35 ÷ 31.55
8		15	27.40	2.52	23.90 ÷ 30.90
9		20	23.42	2.44	20.03 ÷ 26.81
10		40	21.42	1.52	19.3 ÷ 23.53
11	AlSi12NiCu	5	28.58	2.73	24.79 ÷ 32.37
12		10	28.14	2.48	24.70 ÷ 31.58
13		15	27.67	1.87	25.08 ÷ 30.26
14		20	21.00	1.81	18.44 ÷ 23.56
15		40	20.96	2.26	17.82 ÷ 24.10

1) hold time of joints exposed to brazing temperature of 605±5°C

2) x – average value of 5 measurements

Sx – standard deviation

PU – average confidence interval for confidence coefficient 0.95 PU

TABLE 3

Shear strength of joints: stainless steel (X10CrNi18-8) – aluminium (EN-AW1050A) induction brazed in air atmosphere

No.	Joined materials	Filler metal	Shear strength1), MPa		
			x	Sx	PU
1	stainless steel X10CrNi18-8 - aluminium EN-AW1050A	AlSi12	25.0	1.11	23.46 ÷ 26.54
2		AlSi12Ni	30.92	2.44	27.53 ÷ 34.31
3		AlSi12NiCu	30.71	2.34	27.46 ÷ 33.96

1) x – average value of 5 measurements

2) Sx – standard deviation

3) PU – average confidence interval for confidence coefficient 0.95

All the specimens underwent breaking on the aforesaid border.

4. Conclusions

1. The highest shear strength i.e. approx. 30MPa as well as good quality are characteristic of the joints made of the X10CrNi18-8 stainless steel and EN-AW1050A aluminium, induction brazed in air atmosphere at a temperature of 605 ± 5 °C and hold time of approx. 2 ± 3 s, made with AlSi12%Ni4.82% and AlSi12%Ni4.04%Cu2.87% braze alloys and with the use of fluoroaluminate flux.
2. From the viewpoint of the shear strength and quality of joints made of stainless steel and aluminium, the most convenient technological conditions of furnace brazing in argon atmosphere, with the use of AlSi12%, AlSi12%Ni4.82% and AlSi12%Ni4.04%Cu2.87% silumin braze alloys and fluoroaluminate flux are as follows: brazing temperature of 605 ± 5 °C and hold time of 3 ± 15 min (at the aforesaid brazing temperature).
3. The structural metallographic analysis of the joints of stainless steel and aluminium, brazed with AlSi12%, AlSi12%Ni4.82% and AlSi12%Ni4.04%Cu2.87% braze alloys, exposed to brazing temperature at various hold times, revealed the formation of brittle solid solution layers based on $FeAl_3$, $FeSi_2Al_3$ and (NiFe)-Al intermetallic phases; the aforesaid layers

were formed on the steel side and proved decisive for mechanical properties of the joints.

4. The structural examination of the brazed joints of stainless steel and aluminium revealed the formation and growth of the layer of $FeSi_2Al_3$ phase. The said layer was formed if the joined elements were exposed to brazing temperature at hold times of 3s to 15min. It was also observed that exceeding the 15-min hold time resulted in the formation of another continuous layer, based on the FeAl3 phase. The latter layer was responsible for significant reduction of the shear strength of the joints.
5. In the joints brazed with braze alloys containing nickel, it was possible to observe the formation and growth of the $FeSi_2Al_3$ layer as well as a layer based on the (NiFe)-Al phase; the latter layer was formed on the joint side. The total thickness of both of these layers, particularly at a hold time exceeding 15min, was comparable to the thickness of the layer of the $FeSi_2Al_3$ phase in the joints made with the AlSi12 braze alloy (without nickel).

REFERENCES

[1] Joint publication. Brazing Handbook. AWS, Miami, Floryda, 5 ed., 378 (2007).

[2] N. F. Laško, S. V. Laško, Pajka metałłov. Mašinostrojenie, Moskva. 297-299 (1984) (in Russian).

[3] K. Saiola, K. W. Song, K. Nishimoto, Lectures of International Conference "Brazing, high temperature brazing and diffusion bonding" Aachen 1-6 (2004).

[4] K. Kimapong, T. Watanabe, Welding Journal **10**, 277-282 (2004).

[5] P. D. Calderon, D. R. Walmsley, Z. A. Munir, Welding Journal **4**, 104-112 (1998).

[6] C. Thomy, A. Wirth, M. Kreimeyer, F. Wagner, F. Vollertsen, Welding on the World **51**, 7, 311-326 (2007)

[7] M. Roulin, J. W. Luster, C. Karadeniz, A. Mortensen, Welding Journal **5**, 151-155 (1999).

[8] E. Lugscheider, K. Schlimbach, Lectures of International Conference "Brazing, high temperature brazing and diffusion bonding" Aachen, 191-195 (1998).

[9] S. Liu, A. Suzumura, T. T. Keshoi, T. Yamazoki, JSME International Journal **48**, 420-425 (2005).

[10] L. Peng, L. Yajiang, W. Juan, G. Jishi, Materials Research Bulletin **38**, 1493-1499 (2003).

[11] A. K. Kurakin, Fizika Metallov i Metalloviedienie **30**, 1, 105-110 (1970) (in Russian).

[12] R. B. Bhagat, Journal of Material Science. **24**, 1496-1502 (1989).

[13] Y. H. Hwanh, C. Hornig, S. J. Lin, K. S. Liu, Journal of Material Science **32**, 719-725, (1997).

[14] A. Pottinaih, A. Lawley, Metallurgical. Transaction. **5**, 1, 111-119 (1974).

[15] T. Massalski, Binary alloy phase diagrams. ASM, Metals Park, Ohio, 1991.

[16] P. Villars, A. Prince, H. Okamoto, Handbook of tenary alloy phase diagrams. ASM International, Materials Park, Ohio, 1995.

[17] A. Winiowski, Badania materiałowo – technologiczne lutowania aluminium ze stalą nierdzewną i miedzią (Technological investigations of brazing aluminium to stainless steel and cooper). Praca badawcza statutowa Instytutu Spawalnictwa (Research output of Institute of Welding – Gliwice) nr Cc-49/ ST-180.1 / 2001 (no published). Andrzej Winiowski Instytut Spawalnictwa-Gliwice

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