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Adjustment of Process Parameters in the Brazing of Aluminium Heat Exchangers

Abstract: Brazing in tunnel continuous furnaces constitutes the primary technology used when brazing heat exchangers made of the 3XXX series of aluminium alloys. The pure nitrogen-shielded brazing process is performed using non-corrosive flux Nocolok. The primary parameters applied during the brazing of aluminium heat exchangers include brazing temperature and time as well as the type and the amount of filler metals. One of the most commonly used brazing metals (having the form of coatings deposited on elements subjected to brazing) is silumin AlSi7.5. All parameters, significantly affecting the quality of the brazing process, enable the prevention of unfavourable physicochemical phenomena such as the dissolution and the erosion of brazed joints. The article presents results of brazing tests performed using normal, hot and very hot temperature profiles. A wedge test discussed in the article (performed using the normal brazing profile and involving metallographic examination) enabled the determination of the capillarity and wettability of the filler metal. The test also revealed the slight dissolution of materials subjected to brazing, yet within acceptable limit values.

Keywords: brazing, heat exchangers, aluminium alloys, aluminium 3XXX series

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Most heat exchangers manufactured in the automotive industry (Fig. 1) are made of aluminium alloys using the brazing technology. As regards the brazing of aluminium alloys, the difference between the liquidus temperature of silumin brazing metals and the temperature of materials subjected to brazing is relatively low and restricted within the range of 35°C to 65°C. However, the above-presented situation may create may technological problems when joining aluminium components of heat exchangers [1]. Important brazing-related aspects include the heat exchanger design, materials used in the production of the exchanger as well as processes such as the preparation of elements, the fixing of exchangers and the adjustment of optimum brazing parameters [2, 3]. The primary technological parameters concerning the brazing of aluminium heat exchangers include the time and the temperature of the brazing process as well as the type and the amount of filler metals (particularly the thickness of the filler metal coating). All of the above-named parameters significantly affect the quality of the brazing process and make it possible to prevent unfavourable physicochemical phenomena such as the dissolution and the erosion of brazed joints [3].

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Base materials and filler metals used in the production of heat exchangers

Materials used in the production of heat exchangers applied in the automotive industry are modified aluminium alloys, originally designated as EN AW – 3003 (AlMn1Cu), EN AW – 3005 (AlMn1Mg0.5) and EN AW – 6060 (AlMgSi). Aluminium alloys of the 3XXX group (e.g. EN AW – 3003 and EN AW – 3005), the primary dissolution component of which is manganese, often, when combined with magnesium, enable the obtainment of significantly superior mechanical parameters (particularly at higher temperature) in comparison with those obtainable using unalloyed aluminium EN AW – 1050A. The aforesaid alloys are also characterised by high plasticity, very high corrosion resistance as well as good weldability and brazeability. Because of the aforesaid advantages, customised aluminium alloys of the 3XXX group are most commonly used in the manufacturing of heat exchangers [5]. The chemical compositions of base materials used in the tests discussed in the article are presented in Table 1. The most popular brazing metal is silumin alloy AlSi7.5 (having a melting point restricted within the range of 577°C to 613°C), the chemical composition of which is presented in Table 2. The filler metal is deposited (as a coating) on the base material strip. The thickness of the filler metal layer usually constitutes between 5% and 15% of the entire strip (foil) thickness.

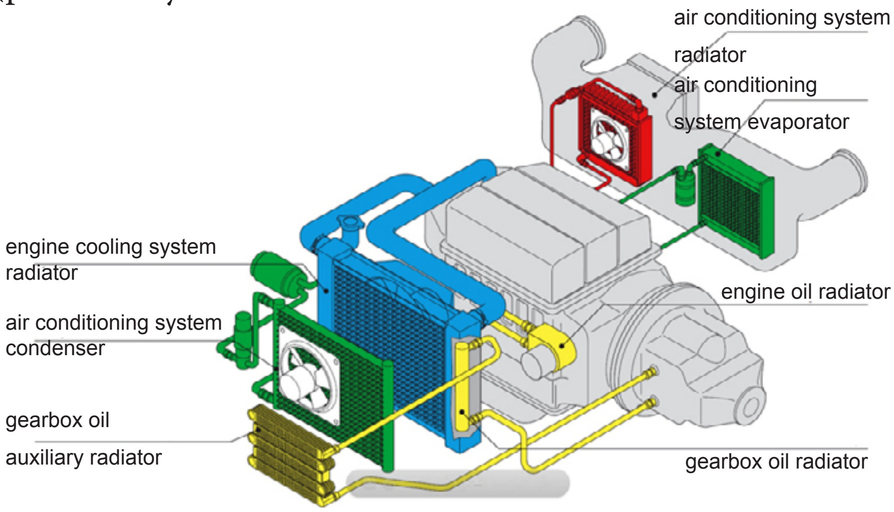

Fig. 1. Heat exchangers present in the car [4]

Table 1. Chemical compositions of the base materials used in the experimental tests (according to data provided by the producer and specified in related material conformity certificates)

Material designation	Chemical composition, % by weight										
	Source	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Oth.
EN AW–3003 (modified) (AlMn1CuMg0.05)	prod.	bal.	0.00 ÷ 0.60	0.00 ÷ 0.70	0.05 ÷ 0.20	1.00 ÷ 1.50	0.00 ÷ 0.05	–	–	0.00 ÷ 0.10	–	0.00 ÷ 0.15
	cert.	bal.	0.45	0.51	0.07	1.20	0.05	0.002	–	0.01	0.033	–
EN AW–3003 (modified) (AlMn1CuMg0.3)	prod.	bal.	0.60 ÷ 0.84	0.40 ÷ 0.60	0.40 ÷ 0.64	1.10 ÷ 1.40	0.20 ÷ 0.30	–	–	0.00 ÷ 0.05	–	0.0 ÷ 0.15
	cert.	bal.	0.81	0.55	0.58	1.25	0.23	0.007	0.003	0.02	0.12	–
EN AW–3003 (modified) (AlMn1CuZn1.5)	prod.	bal.	0.50 ÷ 1.00	0.00 ÷ 0.70	0.00 ÷ 0.10	1.40 ÷ 1.80	–	–	–	1.20 ÷ 1.80	–	0.00 ÷ 0.15
	cert.	bal.	0.78	0.26	0.01	1.59			–	1.53		–
EN AW–3005 (modified) (AlMn1CuMg0.4)	prod.	bal.	0.00 ÷ 0.60	0.00 ÷ 0.70	0.20 ÷ 0.40	1.00 ÷ 1.50	0.10 ÷ 0.40	0.00 ÷ 0.10	–	0.00 ÷ 0.10	0.00 ÷ 0.10	0.00 ÷ 0.15
	cert.	bal.	0.04	0.18	0.01	1.15	0.22	0.01	–	0.01	0.03	–

Table 2. Chemical composition of brazing metal AlSi7.5 used in the tests (in accordance with PN-EN 573-3:2014-02 and a related material conformity certificate)

Brazing metal designation	Chemical composition, % by weight											
	Source	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Oth.
EN AW–4343 (AlSi7.5)	prod.	bal.	6.80 ÷ 8.20	0.00 ÷ 0.80	0.00 ÷ 0.25	0.00 ÷ 0.10	–	–	–	0.00 ÷ 0.20	–	0.00 ÷ 0.15
	cert.	bal.	7.90	0.22	0.00	0.00	0.001	0.001	0.002	0.01	0.005	–

All the brazing tests were performed using non-corrosive flux Nocolok (inorganic fluoride salt $K_{1-3}AlF_{4-6}$). The flux was applied using the electrostatic painting method, i.e. by spraying the mixture of electrostatically charged particles of Nocolok with air or by spraying thermally fixed slurry (the so-called Paint Flux method), being the mixture of flux, water and adhesive [4, 6].

Brazing tests

The brazing tests were performed in the tunnel continuous furnace in a nitrogen atmosphere (nitrogen purity being 99.999%) (5.0). The schematic diagram of the furnace is presented in Figure 2.

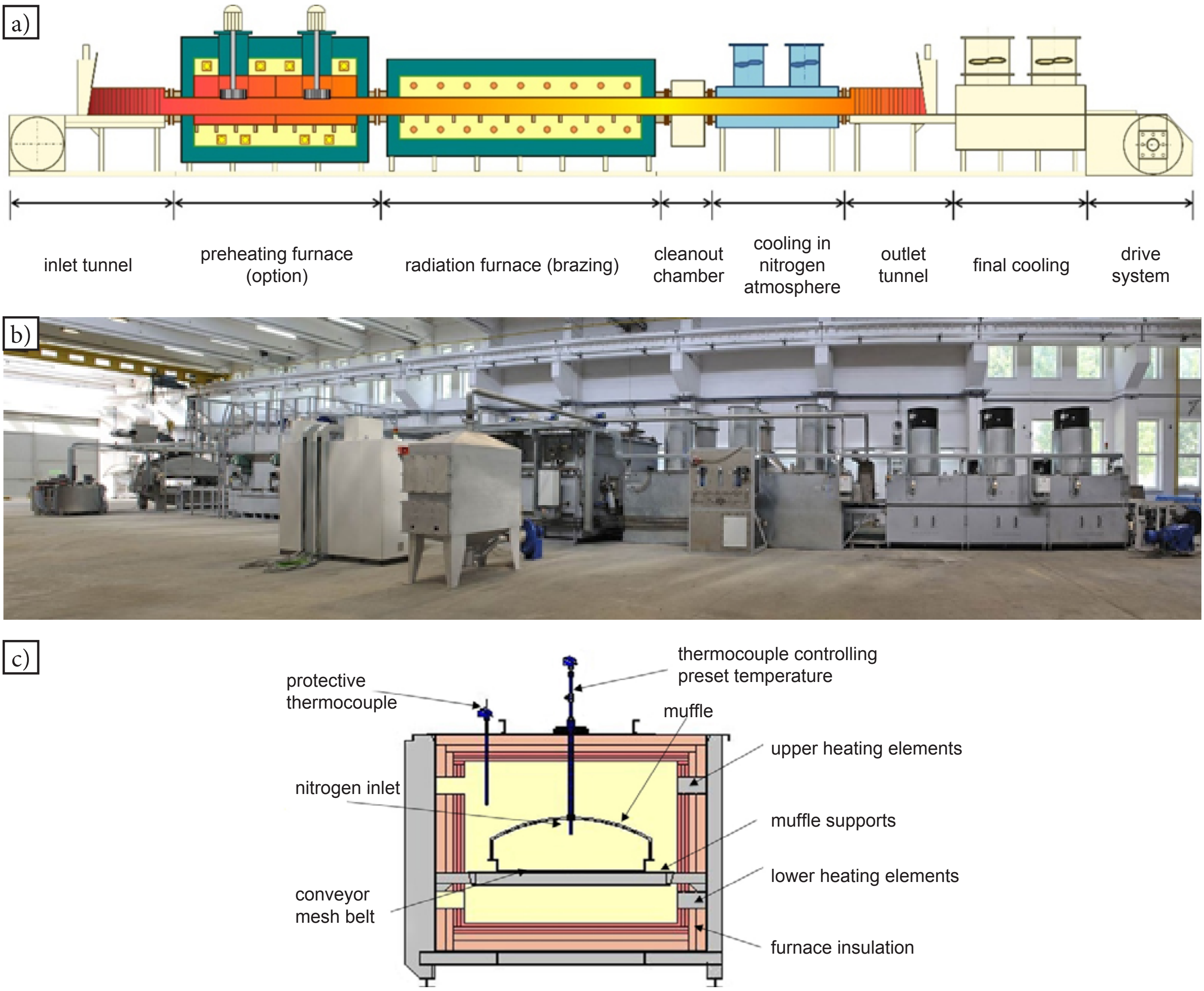

Fig. 2. Schematic diagram of the tunnel continuous furnace used for the brazing of aluminium heat exchangers [7] (a), CAB tunnel continuous furnace (SECO/WARWICK) [8] (b), CAB tunnel continuous furnace in cross-section [8] (c)

The brazing tests involved the application of 3 temperature profiles designated as follows:

- normal profile with a maximum temperature of approximately 603°C, a hold time of approximately 5 minutes at a temperature of more than 577°C,
- hot profile with a maximum temperature of approximately 615°C, a hold time of approximately 10 minutes at a temperature of more than 577°C,
- very hot profile with a maximum temperature of approximately 626°C, a hold time of approximately 21 minutes at a temperature of more than 577°C.

Dissolution and erosion of brazed joints

Parameters applied in the brazing of aluminium heat exchangers should be adjusted in a manner making it possible to obtain joints filled with the brazing metal and, at the same time, prevent the occurrence of such adverse phenomena as dissolution or erosion.

The dissolution of the base material results from its interaction with the liquid filler metal, i.e. through the diffusion of silicon from the liquid brazing metal to the material subjected to brazing [9], which, in turn, reduces locally the meting point of a material subjected to brazing and, consequently, dissolution. During the above-presented phenomenon, diffusion also takes place in the reverse direction, i.e. from the base material to the filler metal. Unlike erosion, the dissolution process is "static" in nature, where its scale and intensity depend on the value of maximum temperature, brazing time and the type of a brazing metal used in the process.

Erosion constitutes the aggressive effect of the brazing metal leading to the reduction of the base material thickness [10 - 12] and results from the migration of the filler metal on surfaces of elements being joined. The intense flow of the brazing metal tears the material off (probably atom after atom) [11]. In the aforesaid case, the effect is connected with the more dynamic interaction between the brazing metal and the base material [7, 13]. The aforesaid flow may be triggered by gravity, differences in surface tension or high temperature gradient [11, 14].

Both phenomena may lead to characteristic consequences affecting brazed joints. The notion of dissolution is concerned with the change of the structure of the material subjected to brazing. The geometry of the entire joint does not change as the fragment of the original material is filled with the mixture of the brazing metal and of the material subjected to the brazing process (Fig. 3a). In turn, the notion of erosion represents a situation, where (during brazing) the thickness of the base material is reduced through the effect of the liquid brazing metal, which, in turn, triggers a change of the joint geometry (Fig. 3b). Metallographic tests of the brazed joints were performed using an Eclipse LV150 light microscope (Nikon).

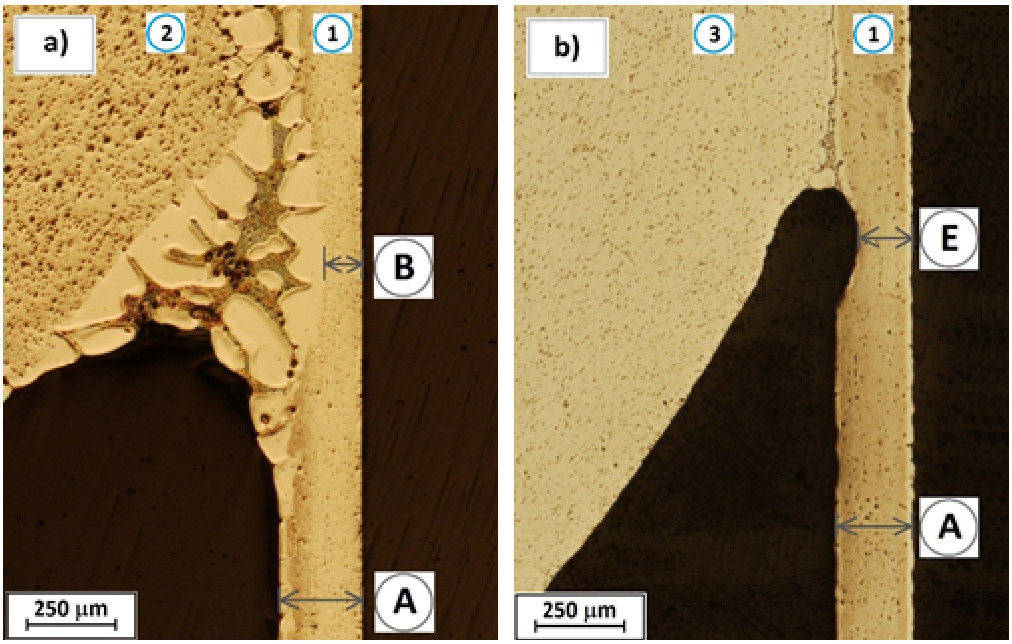

Fig. 3. Brazed joints in heat exchangers and the phenomenon of dissolution (a) – brazing metal AlSi7.5 and erosion (b) – brazing metal AlSi7.5; designation of aluminium alloys: AlMn1Cu (1) AlMn1CuMg0.5 (2) and AlMn1(3); etchant: 0.5% HF solution

The joint presented in Figure 3a was brazed using the very hot temperature profile, whereas joint presented in Figure 3b was brazed using the normal temperature profile.

The quantitative analysis of both phenomena (relative value of dissolution and of erosion) can be expressed as follows [3, 7]:

$$alloying = \frac{(A-B)}{A} \cdot 100\% \qquad (1)$$

A – nominal thickness of a material subjected to brazing, *B* – thickness of the material in the area characterised by the greatest dissolution-triggered thickness reduction (Fig. 3a),

$$erosion = \frac{(A-E)}{A} \cdot 100\% \qquad (2)$$

E – thickness of the material in the area characterised by the greatest erosion-triggered thickness reduction (Fig. 3b).

Depending on types of joints, types of heat exchangers and required operating regime, both industrial standards and internal procedures developed by producers of heat exchangers specify acceptable relative values of dissolution and, sometimes, of erosion. Usually, dissolution values permissible in industries are restricted within the range of 20% to 30%; in exceptional cases the aforesaid value could reach as many as 50%. The above-presented dissolution-related limit values result primarily from the deterioration (reduction) of mechanical properties of brazed joints, revealed during tests performed when accepting designs of heat exchangers (particular in terms of changes of the temperature and/or pressure of the coolant). The phenomenon of dissolution does not change the geometry of the joint (as the depleted material is replaced (filled) with the brazing metal). However, dissolution leads to changes of the structure of the material and, consequently, changes of its mechanical properties.

In turn, in terms of qualitative assessment, erosion is unacceptable and treated as a brazing defect disqualifying the use of heat exchangers at subsequent stages of production. However, in exceptional cases the erosion of the heat exchanger may by accepted, provided it is restricted within the maximum range of 10% to 20%.

Assessment of brazeability

The assessment of brazeability was based on the wedge test, making it possible to obtain information about the results of numerous physicochemical phenomena taking place during the brazing of various (particularly dissimilar) materials. The wedge test is used to identify the capillarity of the brazing metal and the wettability of materials with the brazing metal [3, 15, 16]. The method also enables the determination of the optimum gap width [3, 15, 17] in terms of the crystal structure of the joint and the presence/absence of brazing imperfections.

Figure 4 contains the schematic diagram presenting the wedge test in the brazing of aluminium materials (B C). Material C was coated with the brazing metal on the side to be joined with material B; the surface of the aforesaid side was covered with flux Nocolok applied using the Paint-Flux method.

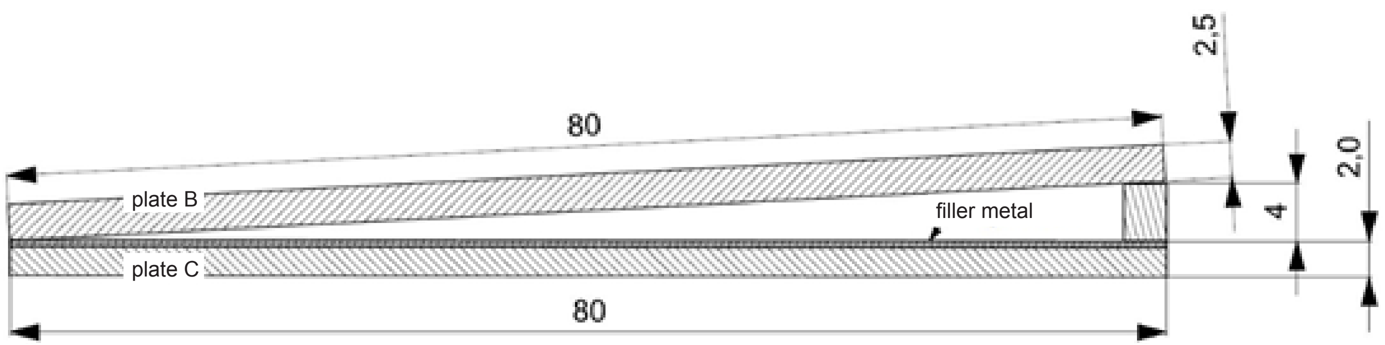

Fig. 4. Preparation of the test elements for the wedge test

Table 3. Wedge test-related information

Plate designation	Base material grade	Plate thickness, mm	Filler metal grade	Nominal thickness of the filler metal, mm (%)
Upper plate B	EN AW–3003 (modified) (AlMn1CuMg0.05)	2.5	–	0 (0)
Lower plate C	EN AW–3003 (modified) (AlMn1CuMg0.3)	2.0	EN AW–4343 (AlSi7.5)	0.1 (5.0)

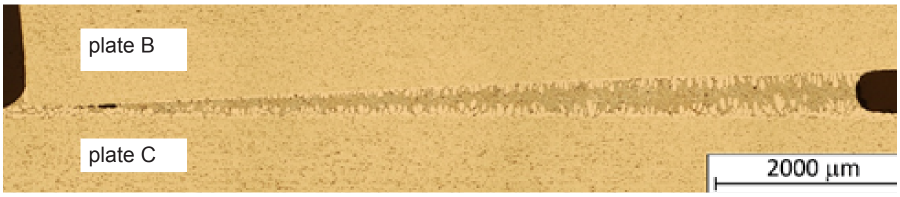

Fig. 5. Wedge test of the C-B joint; etchant: 0.5% HF solution

Information concerning the preparation of materials for the wedge test is presented in Table 3. The brazing process involved the use of plates having dimensions of 80 mm x 25 mm x 2.5 (2.0) mm. Before the application of the flux, the surface of the elements was only subjected to thermal degreasing. The surface was not subjected to any other preparation procedures. During the wedge test, the elements to be subjected to brazing were initially joined using the TIG welding process and tack welds. As a result, a gap having a width of 0.05 mm was formed at the beginning of the joint. The wedge test was performed using the normal brazing profile. The cross-section of the braze joints is presented in Figure 5.

The total length along which the gap was filled with the brazing metal amounted to 8.8 mm. The width of the gap at the end of the braze (in the C-B joint) amounted to 513 µm, thus indicating the filling of the non-capillary gap having a width of more than 0.5 mm. The brazed joint contained some brazing imperfections, such as the lack of continuity (of the braze) as well as the presence of gas pores and post-flux slag inclusions. However, the above-named imperfections were mostly present in the gap having the width exceeding 150 µm.

The microscopic tests (LM) of the braze revealed the presence of the typical microstructure of hypoeutectic silumin (Fig. 6) [9, 18], containing grains of phase α-Al and characterised by hardness restricted within the range of 48 HV0.05 to 53 HV0.05 as well as the presence of the acicular eutectic mixture (α + Si) characterised by a hardness of 93 HV0.05. In the gap having a width of 150 µm and 300 µm, the greater amount of the α-Al phase precipitates was visible on the side of the material provided with the filler metal coating (lower plate C; Fig. 6a, b). In the wider gap having a width of 500 µm (Fig. 6c), the amount of the precipitates of the α-Al solid solution was comparable both on the side of the material provided with the filler metal coating and on the side of the material which was not coated.

The gap having a width of 150 µm contained globular grains of phase α-Al. In turn,

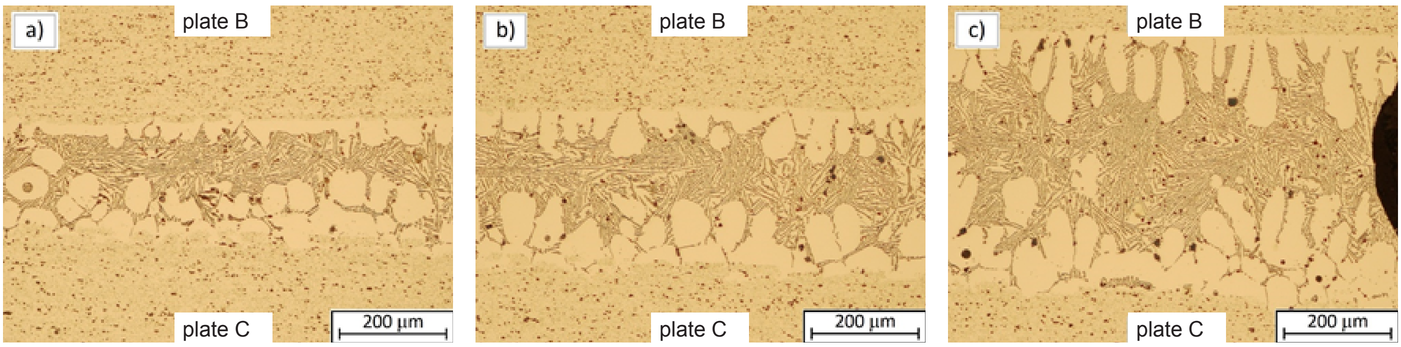

Fig. 6. Microstructure of the joint in the wedge test in relation to the gap having a width of 150 µm (a), 300 µm (b) and 500 µm (c); etchant: 0.5% HF solution

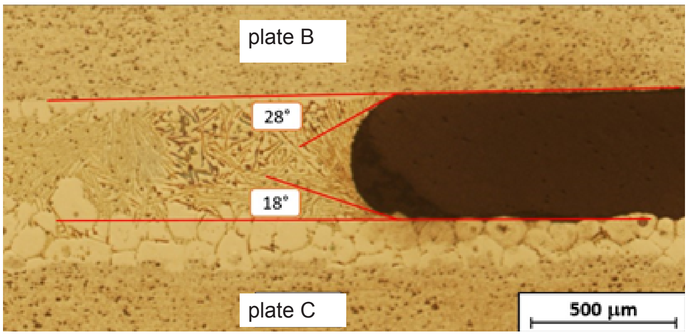

Fig. 7. Identification of contact angles in the wedge test; etchant: 0.5% HF solution

in relation to an increase in the gap width, particularly as regards a width of 500 μm, it was possible to observe columnar precipitates of phase α-Al, growing in the direction of heat propagation [18, 19].

The measurements of the contact angle of the materials subjected to brazing are presented in Figure 7. In relation to the lower plate (C), coated with the brazing metal, the average value of the contact angle (based on 8 measurements) amounted to 18°. In relation to the upper plate (B), not coated with the brazing metal, the contact angle was greater and amounted to 28°. In spite of the varying wettability between the lower and upper plates, all of the values of the contact angle were below 30°, i.e. characteristic of the good wettability of materials with the brazing metal.

Dissolution values were calculated using formula (1). In relation to the plates coated with the brazing metal, the value of dissolution amounted to approximately 4%. In turn, in relation to the plates not coated with the brazing metal, the value of dissolution did not exceed 1.5%. The relatively low intensity of the dissolution process was the result of the low maximum brazing temperature in the wedge test and the short hold time at temperature above 577°C.

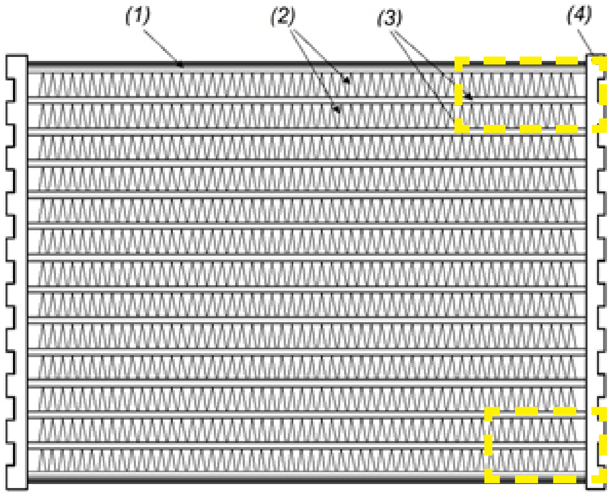

Fig. 8. Heat exchanger illustrated with an example of the combustion engine radiator core: clamp (1), cooling strip (2), pipe (for coolant) (3) and grid plate (4); areas subjected to the tests are marked yellow

Brazing of the combustion engine radiator

The effect of brazing parameters (based on production at the Mahle Behr company from Ostrów Wielkopolski) was illustrated using the radiator core of the combustion engine cooling system (Fig. 8). Table 4 presents materials used in the production of the radiator.

Flux Nocolok was applied on the surface of the materials using the electrostatic method.

Table 4. Materials used in the production of the radiator

Element	Base material grade	Material thickness, μm	Number of coating layers	Brazing metal coating	Nominal thickness of the brazing metal coating, μm
Clamp	EN AW–3003 (modified) (AlMn1CuMg0.05)	1490	1	EN AW–4343	74.5
Cooling strip	EN AW–3003 (modified + 1.5% Zn) (AlMn1CuZn1.5)	75	0	lack	0
Pipe for coolant	EN AW–3005 (modified) (AlMn1CuMg0.4)	250	2	EN AW–4343	36
Grid plate	EN AW–3003 (modified) (AlMn1CuMg0.05)	1490	1	EN AW–4343	74.5

It should be noted that neither hot nor very hot brazing profile is usually used in the brazing of the cores of the heat exchangers of the combustion engine radiator. The above-named temperature profiles were used for comparative purposes – to assess the effect of increased brazing parameters on the occurrence of such phenomena as dissolution and erosion. Figure 9 presents a fragment of the heat exchanger in relation to the clamp connection, the cooling strip, the pipe for coolant and the three brazing (temperature) profiles.

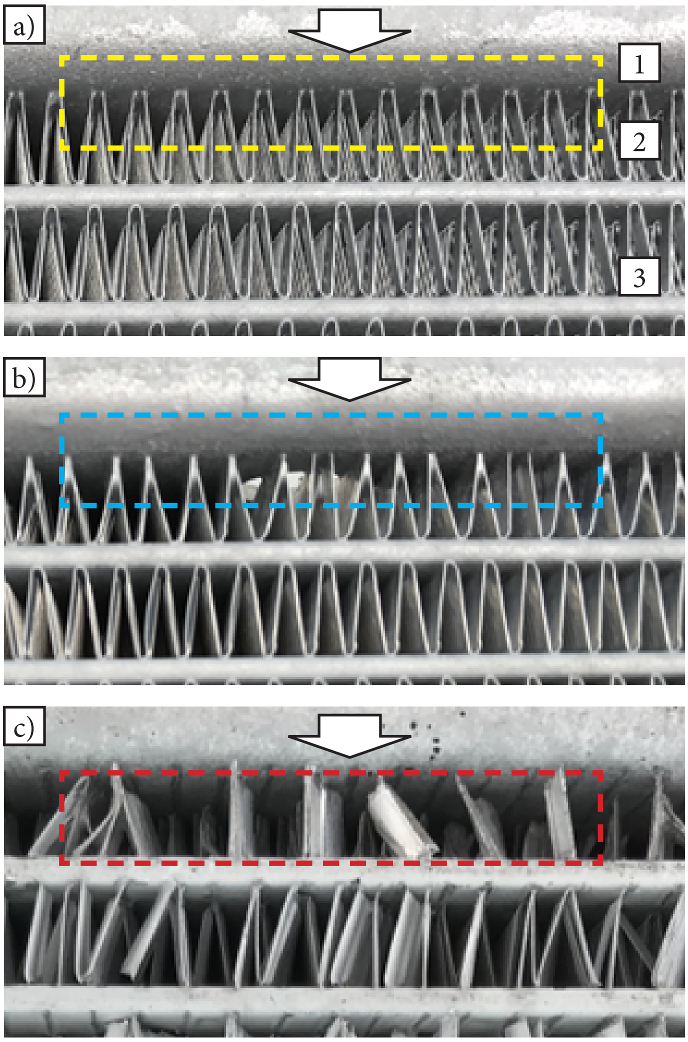

Fig. 9. Fragments of the heat exchanger (from Fig. 8) after the brazing process in relation to normal (a), hot (b) and the very temperature profile (c); designation of the elements: clamp (1), cooling strip (2) and pipe (for coolant) (3)

In relation to the normal brazing-related temperature profile it was possible to observe the only slight dissolution of the cooling strip in the areas of contact with the clamp (orange framing). In relation to the hot temperature profile it was possible to observe the partial erosion of the cooling strip at the clamp (blue framing). In turn, no changes were observed as regards the joint of the cooling strip with the pipe in relation to the normal and hot brazing-related temperature profiles. In relation to the very hot temperature profile it was possible to observe significant damage to the cooling strip, particularly significant at the clamp (red framing). In relation to the very hot profile, all the surfaces of the heat exchanger were mat. The aforesaid phenomenon was significantly less intense in relation to the hot profile. In turn, no changes of the heat exchanger surfaces were observed in relation to the normal brazing profile.

Figure 10a–c presents the following brazed joints: pipe for coolant – cooling strip – clamp in the radiator, in relation to the 3 temperature profiles of the brazing process. Both as regards the hot and the very hot profile, the maximum brazing temperatures exceeded the liquidus

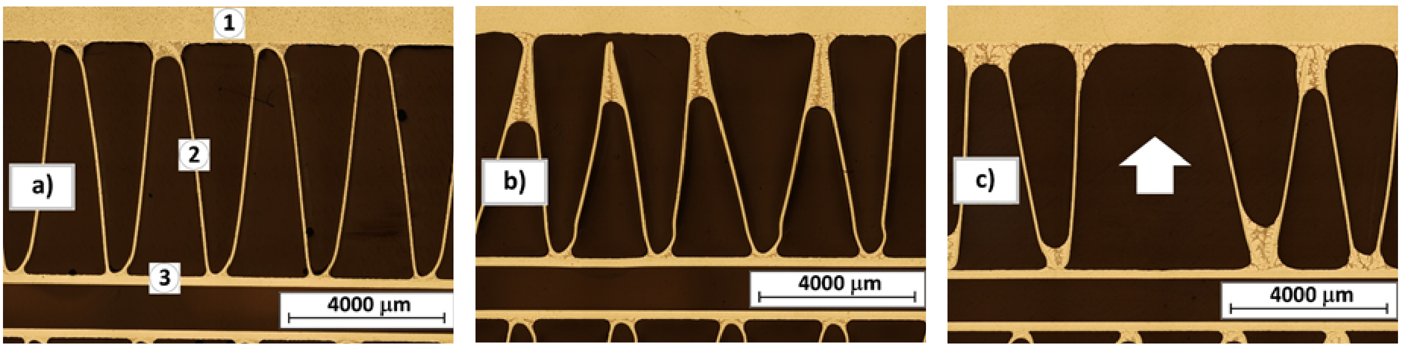

Fig. 10. Brazed joints in the heat exchanger: pipe (for coolant) – cooling strip – clamp, in the radiator core, in relation to the 3 temperature profiles of the brazing process, i.e. normal (a), hot (b) and very hot (c); the arrow indicates the entire erosion of the cooling strip; designations of elements: clamp (1 – brazing metal AlSi7.5), cooling strip (2) and the pipe for coolant (3 – brazing metal AlSi7.5); etchant: 0.5% HF solution

temperature of the brazing metal, thus intensifying the phenomenon of dissolution and that of erosion.

In all of the cases it was possible to observe the clearly noticeable effect of the thicker coating of the brazing metal on the clamp (74.5 µm – upper elements) in comparison with the thickness of the filler metal coating on the pipe (36 µm – lower elements). Even in relation to the normal (“cool”) temperature profile, the size of the braze as well as the dissolution of the clamp (1) and of the cooling strip (2) were greater than those in relation to the elements in the lower joints. In relation to the hot profile it was possible to observe the erosion of the cooling strip on the clamp side; the joint being proper on the pipe side. In relation to the very hot profile it was possible to observe erosion on both sides of the cooling strip (yet mainly as a result of the migration of the filler metal from the clamp), where some fragments of the cooling strip had disappeared entirely, alloyed by the liquid filler metal. In addition, erosion did not occur in relation to all of the joints between the pipe (3) and the cooling strip (2) (Fig. 10). The aforesaid phenomenon did not depend on the temperature profile. However, in relation to both hot profiles it was possible to observe

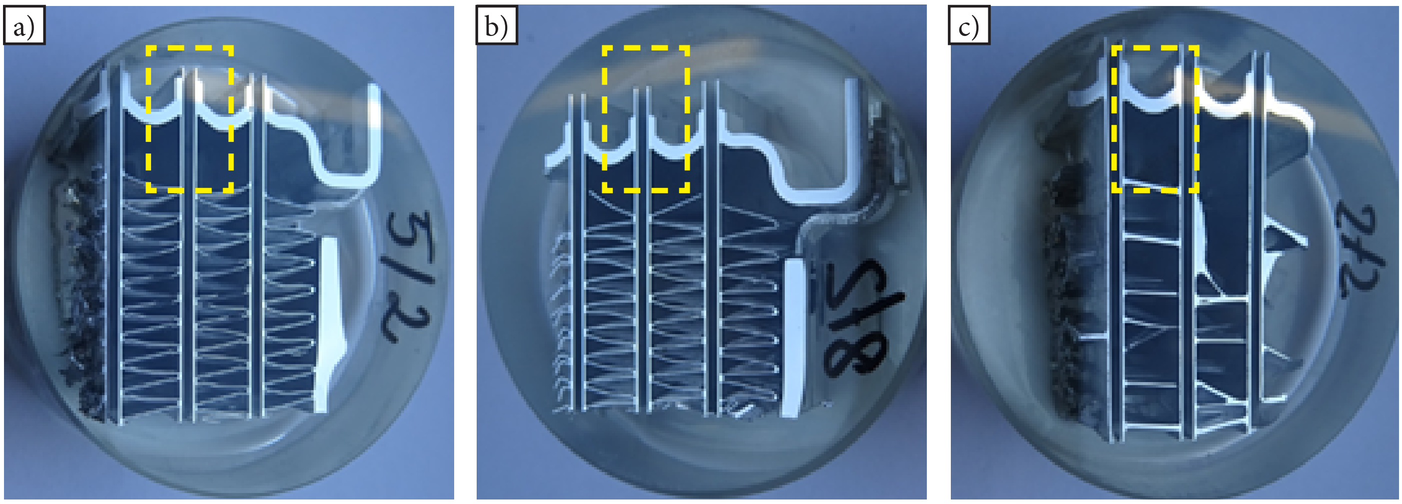

Fig. 11. Cross-sections of the brazed joints in the heat exchangers: pipe – grid plate in the radiator, in relation to the 3 temperature profiles of the brazing process, i.e. normal (a), hot (b) and very hot (c)

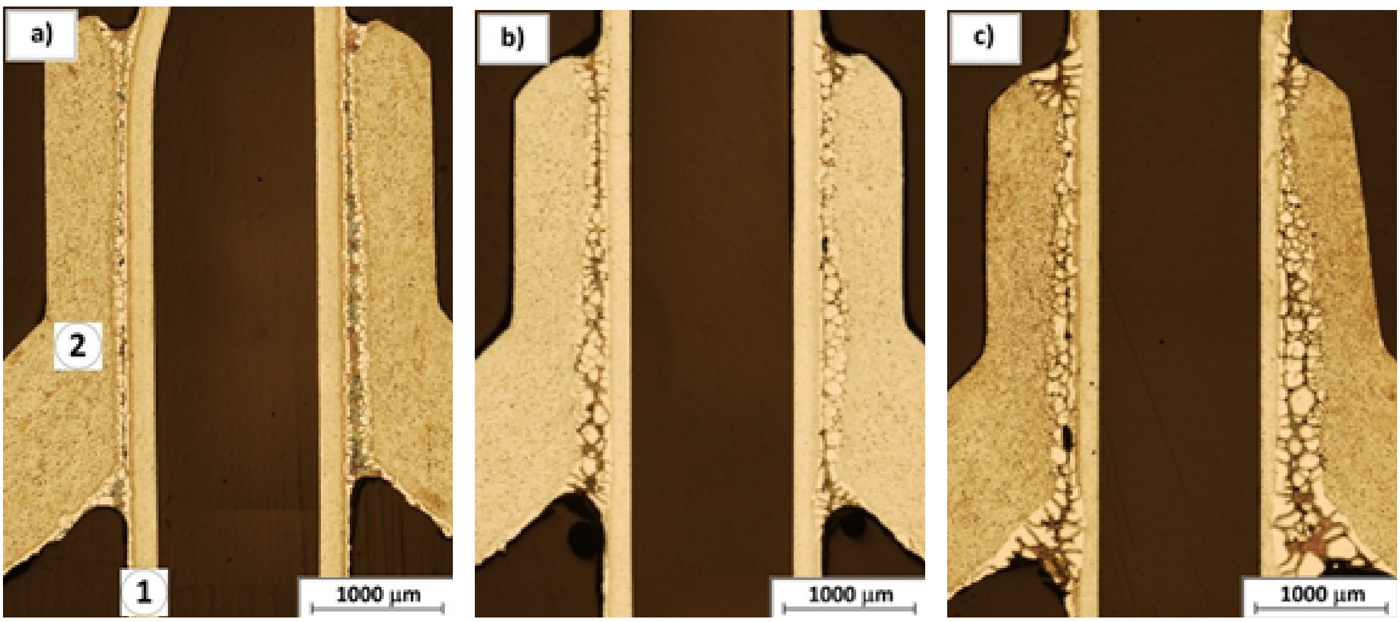

Fig. 12. Macrostructures of the welded joints in the heat exchangers: pipe – grid plate in the radiator, in relation to the 3 temperature profiles of the brazing process, i.e. normal (a), hot (b) and very hot (c); designations of elements: pipe (1), grid plate (2), brazing metal AlSi7.5); etchant: 0.5% HF solution

the significant dissolution of the materials subjected to brazing. Based on the above-presented test results it is recommended that the thickness of the filler metal coating applied on the clamp should be reduced by more than twice, i.e. from 74.5 µm to approximately 36 µm.

Figures 11 and 12 present the cross-sections and the macrostructures of the joints between the pipe and the grid plate respectively. It is possible to observe that an increase in brazing temperature and time was accompanied by the intensified dissolution of both elements. Figure 11c presents the entire erosion of the cooling strip around the grid plate (as a result of the migration (triggered by excessively high brazing parameters) of the surplus molten brazing metal from the grid plate on the pipe surface). Figure 12 present the change of the braze structure along with an increase in the maximum temperature and time of the brazing process (visible growth of the α-Al phase grains)

Table 5 presents the absolute values concerning the dissolution of the pipe material (having a thickness of 250 µm) and that of the grid plate (of variable thickness) as well as the relative values concerning the dissolution of the pipe material (calculated using formula (1)). In relation to the normal temperature profile, the relative value of pipe dissolution amounted to 18% and did not exceed the maximum permissible value for the exchanger (i.e. 30%). In relation to the hot and very hot temperature profiles, the relative values of pipe dissolution amounted to 38% and 68% respectively, exceeding the acceptable value. In such situation, the above-presented exchanger (as well as all other exchangers of the same type and batch) should be classified as defective.

Summary

The maximum temperature obtained by the elements made of aluminium alloys EW AW – 3003 or EN AW – 3005 subjected to brazing performed using brazing metal AlSi7.5 significantly intensified the phenomenon of erosion. The brazing temperature should not exceed 610°C, whereas the time of brazing should not exceed 7 min. The above-presented test results justify the conclusion that, apart from the temperature and the time of the brazing process, another very important factor responsible for dissolution and erosion was the amount of brazing metal AlSi7.5 used to fill the brazed joint. The above-named effects were intensified by capillary forces, facilitating the migration of the liquid brazing metal on the heat exchanger surface. An increase in the maximum temperature and that in the hold time at the brazing temperature could be accompanied by the intensification of erosion. In turn, in the areas where the amount of the filler metal was proper, only the dissolution phenomenon was observed. In extreme cases, where the brazed josint was provided with the excessive amount of the filler metal and where both the maximum temperature and the hold time were outside recommended ranges, it was possible to observe a very aggressive interaction between the filler metal and the base material.

Table 5. Values related to the dissolution of the material of the pipe for coolant and the grid plate in relation to individual brazing temperature profiles

Brazing temperature profile	Dissolution of the grid plate, µm	Dissolution of the pipe transporting the coolant, µm	Dissolution of the pipe transporting the coolant, %
Normal	130	40	18
Hot	191	83	38
Very hot	262	151	68

The authors recommend the use of the capillary brazing gap having a width of not more than 150 µm, as characterised by the lower number of welding imperfections than that observed in wider gaps.

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