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DISSOLUTION AND EROSION PHENOMENA IN THE BRAZING OF ALUMINUM HEAT EXCHANGERS

On the basis of research, the mechanisms of dissolution and erosion during brazing of aluminium alloys and the influence of these phenomena on brazed joints of heat exchangers are presented. A number of factors have been identified that affect the formation of these phenomena during brazing aluminium alloys, these include : the maximum temperature and holding time at brazing temperature, and the type and amount of filler metal. The research was supported by examples of dissolution and erosion phenomena during series production of aluminium heat exchangers using three brazing profiles (normal, hot and very hot). It has been found that the dissolution of the engine radiator components during brazing, is from 18 to 68%, depending on the brazing profile used. For a very hot profile, erosion in part of the brazed exchanger, even destroys (removes) thin elements of the cooling fins.

Keywords: filler metal, heat exchanger, brazing, aluminium alloys 3XXX and 4XXX series, dissolution and erosion phenomena

1. Introduction

Brazing of aluminium alloys is currently one of the most commonly used technologies for the production of heat exchangers [1-3]. However, the technology of brazing aluminium and its alloys can generate difficulties during serial production. This is mainly due to either material or process variables, which are a natural phenomenon in the production process [4-6]. As a consequence, it can lead to both the generation of large number of defective products during the manufacturing process itself, as well as a reduction of the assumed working life of the heat exchanger.

This is why the selection of nominal values and tolerances is very important during heat exchanger design [7]. In addition, during manufacture of exchangers, it is necessary to specify the recommended and limit values for key parameters of all technological processes [5,8,9]. Appropriate selection of the above-mentioned parameters should be made during the validation (approval) stage of the design and manufacturing technology of each heat exchanger [10].

One of the most undesirable incompatibilities arising in the brazing process is the local reduction of the thickness of the heat exchanger elements, caused by dissolution and erosion phenomena. This is important, because such a heat exchanger can even obtain positive results of all tests performed during its manufacturing, however under normal operation, it may fail prematurely [4].

The subsequent part of the work presents the mechanisms of dissolution and erosion phenomena occurring during brazing of aluminum heat exchangers. On the basis of the tested examples, the influence of these phenomena on the brazed joint is presented. Additionally, selected factors influencing their formation will be characterized.

2. Materials and methods

For the production of aluminum heat exchangers, the most often used material is in the form of foil, strips or sheets obtained from the rolling process. Core materials can be additionally cladded with interliner or filler metal layers (Fig. 1). In the CAB (Controlled Atmosphere Brazing) technology, silumin (Al-Si) filler metals are used. The addition of Si lowers the melting point of filler metal in relation to the core material [2].

In brazing aluminium heat exchangers, various interactions between the filler metal and the core material can occur. This was seen on the basis of metallographic examinations of brazed joints using a light microscope (LM), type NIKON Eclipse LV150. The metallographic specimens were observed after their chemical etching with 0.5% HF acid solution (Fig. 2a-f).

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Fig. 1. An example of the structure of the material used in manufacture of aluminum heat exchangers

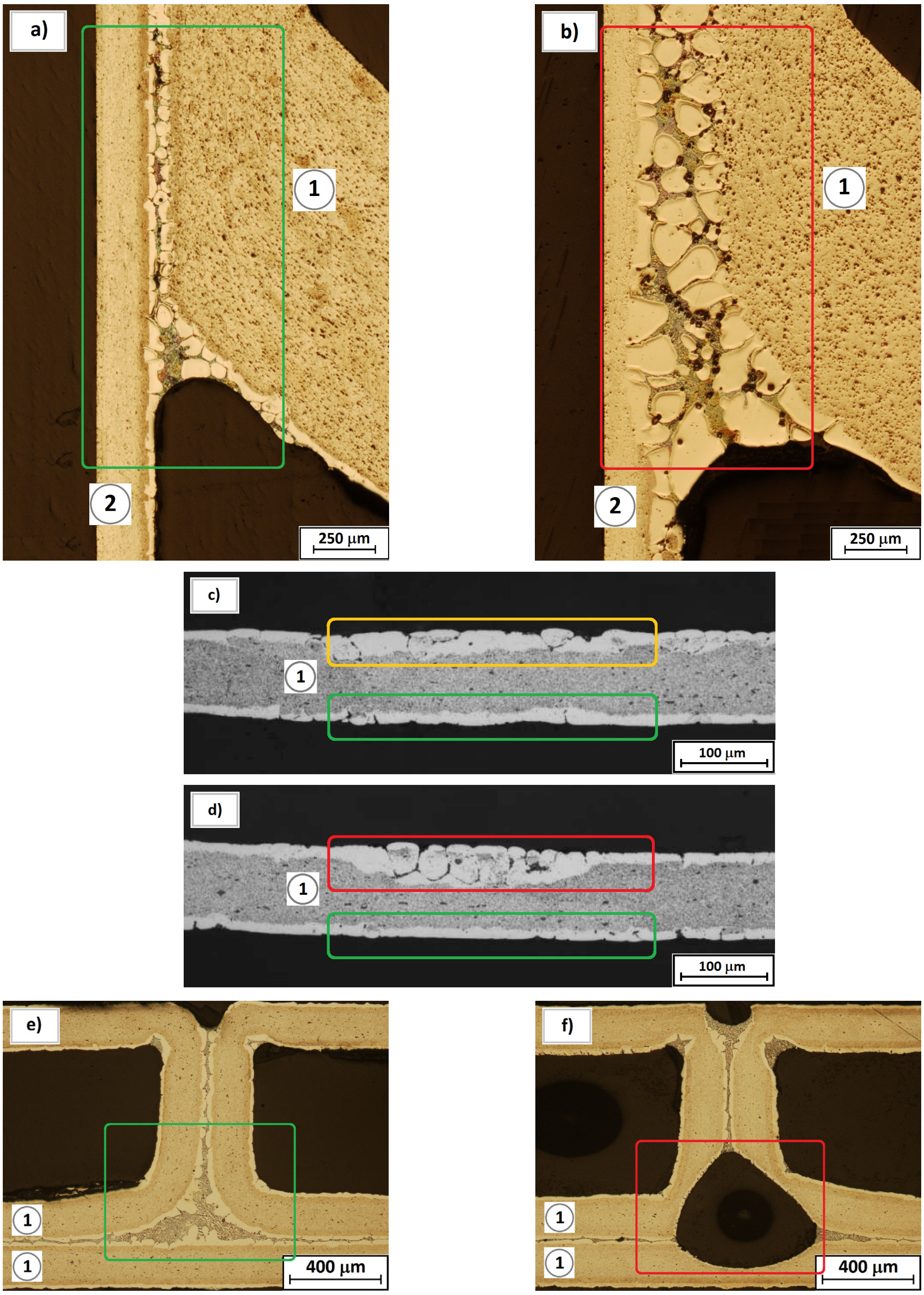

Fig. 2. Examples of interaction between liquid filler metal and core material during brazing of aluminium alloys: a – absence or low intensity of dissolution phenomenon occurrence, b – significant intensity of dissolution phenomenon occurrence, c – absence and medium intensity of LFM phenomenon occurrence, d – absence and significant intensity of LFM phenomenon occurrence, e – absence of erosion phenomenon occurrence, f – significant intensity of erosion phenomenon occurrence. Designation of brazed aluminium alloys: (1) AlMn1Cu, (2) AlMn1Mg0.5; AlSi7.5 brazing filler metal was used for all of the above examples. Colors: green – absence or low intensity of the phenomenon occurrence, orange – medium intensity of the phenomenon occurrence, red – significant intensity of the phenomenon occurrence

Depending on the nature and type of interaction, the following phenomena can be distinguished.

- Dissolution (Fig. 2a-b) of core material due to contact with liquid filler metal. This occurs as a result of the silicon diffusion from liquid filler metal into the core material, which is still in solid state [11]. This leads to a local decrease of the melting point of the core material and as result to its dissolution. Also during this interaction, core material diffusion into the filler metal occurs. The dissolution has static character and its value and intensity depend on the maximum temperature reached, brazing time, and type of filler metal used. Figures 2a-b show examples of cross-sections of brazed joints where the following occurred: small (Fig. 2a) or significant (Fig. 2b) dissolution of the core material, respectively. In the joint filling the gap between the joined elements (Fig. 2b), very large areas of the α phase are visible surrounded by the AlSi (α + Si) eutectic mixture [12]. This may be due to the fact that for brazing elements made of EN-AW3003 (AlMn1Cu) and EN-AW3005 (AlMn1Mg0.5) high-melting filler metal EN AW-4343 (AlSi7.5) were used along with a very hot brazing profile. As a result, large values of maximum temperature and brazing time were achieved.
- Liquid film migration (LFM) (Fig. 2c-d) – this phenomenon is still the subject of research, and in the literature there are many theories describing this issue. One of them describes it as a static interaction, between the core material and the liquid filler metal. During liquid film migration the core material is decomposed as a result of the liquid filler metal rapidly diffusing silicon into the brazed core material [13]. This is due to a change of free energy of the system [14]. This phenomenon begins at a lower temperature than the brazing temperature. The intensity of this phenomenon depends on the degree of cold deformation of the brazed materials, as well as the type of braze aluminium materials. Additionally, the penetration of liquid filler metal into the core material reduces the volume of filler metal that is available for proper joint formation. Instance of the occurrence of LFM has been shown in Figure 2c-d, where the local change in the structure of core material is visible. Figure 2d shows a case where LFM phenomenon is more intensive. In contrast to the phenomenon of dissolution, no characteristic dendritic structure can be observed in this case [15]. Although, large structures separated from the core material are visible which are no longer strongly associated with this material [12,16]. Such places can weaken both mechanical and corrosion resistance of the heat exchanger during its normal operation [11]. Another theory explains this issue as a result of recrystallization of the core material during the brazing process with simultaneous penetration by the liquid filler metal.
- Erosion (Fig. 2e-f) – in the literature is described as the effect of reducing the thickness of core material as a result of filler metal interaction (eroding the core material away) [15,17,18]. Erosion is a phenomenon arising as a result of liquid migration of filler metal on the surfaces of joining elements [17,18]. In effect the core material is dissolved, as a result of filler metal (silicon rich) stream flow, presumably an atom-by-atom process [15]. In this case, this is a dynamic interaction between filler metal and core material [19,20]. The driving force for this flow may be gravity, surface tension difference, or a large temperature gradient [15,21]. Figure 2f shows erosion as a result of dynamic movement of the filler metal. Characteristic round edged channels have been formed in the joining elements [15]. On the other hand, Figure 2e shows a brazed joint of the same area of the heat exchanger, where the erosion phenomenon did not occur.

A diagram of the mechanism of liquid film migration phenomenon is shown in Figure 3. The LFM phenomenon takes place, when a thin layer of liquid filler metal appears at the grain

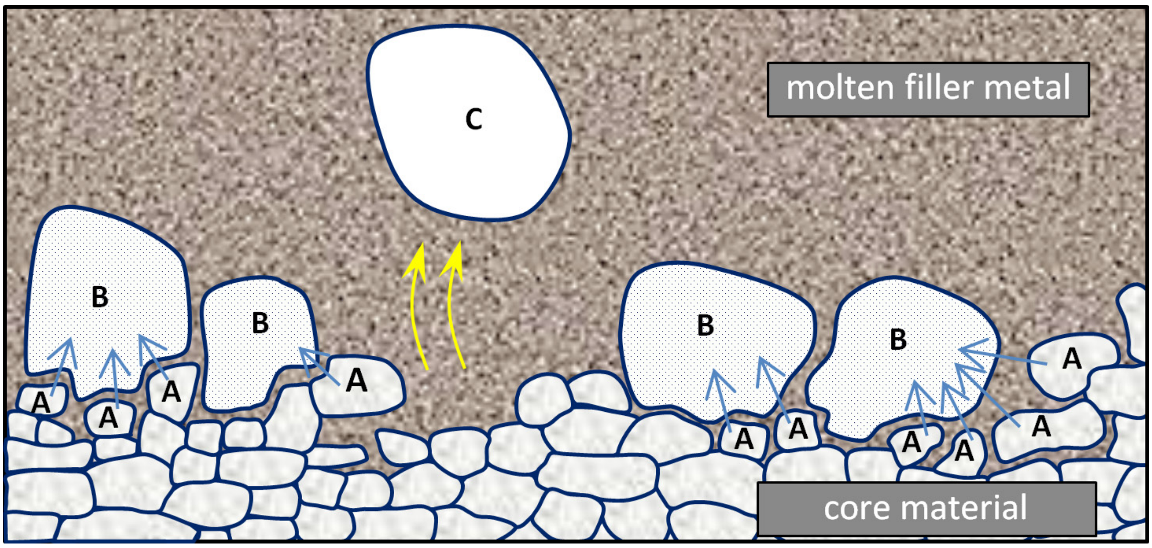

Fig. 3. Diagram of various stages of LFM (Liquid Film Migration) as a result of penetration of liquid filler metal along the grain boundaries of the core material: A – single grains in the material structure, B – larger areas concentrating separated grains, but still adjacent to the structure, C – areas detached from structures moving to the molten filler metal

boundaries of the core material, this layer further penetrates between the boundaries of the deeper grains. This causes subsequent grains (marked as A) to be detached from the core material structure. They join together into larger structures (grains marked as B) and as a result of gravity or convection are moved to the molten filler metal (grains marked as C). This phenomenon is mainly influenced by the structure and chemical composition of the core material used for the construction of a given heat exchanger element [15].

During brazing, a natural phenomenon is when there is a diffusion interaction between the surface of the elements to be joined and the liquid filler metal. This is an undesirable phenomenon. When such an interaction is too strong, it negatively affects the mechanical properties of the brazed materials and / or reduces the corrosion resistance of the heat exchanger [15].

Analyzing the definition of erosion, various terms describing this phenomenon can be found, i.e. dissolution, solubilization, dilution, chemical corrosion, and erosion [11,17]. The first three terms more accurately describe the processes that occur during this phenomenon. Usually in brazing, it is preferable to use the term „erosion", because it describes that something undesirable happened during brazing [17].

In brazing heat exchangers made of aluminium alloys, the terms „dissolution" and „erosion" from the manufacturers point of view, have different meanings in comparison to what was described above. It results that for the above-mentioned phenomena they both describe and additionally qualify the effects arising during brazing. The term „dissolution" refers to decreasing wall thickness of the core material during brazing as a result of a diffusion processes. However, the geometry of the entire joint does not change because the thinned place (wall thickness reduction) of the core material was filled with a mixture of reacted filler metal and joined material (Fig. 4a). In turn, the term of „erosion" describes a situation during brazing where the wall thickness of the core material was reduced due to the action of liquid filler metal and the geometry of the joint was changed (Fig. 4b).

Formulas (1) and (2) represents a quantitative assessment of both phenomena (relative value of dissolution and erosion).

$$dissolution = \frac{(A-B)}{A} \cdot 100\% \tag{1}$$

A – nominal thickness of core material, B – thickness of core material at the place of greatest wall thickness reduction by dissolution

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

A – nominal thickness of core material, E – thickness of core material at the place of greatest wall thickness reduction by erosion

Depending on the type and nature of the joint, the type of heat exchanger, and the required operating conditions, both industry standards and internal procedures of heat exchanger manufacturers specify permissible relative values of dissolution and sometimes erosion. In the case of erosion, this is usually unacceptable from the point of view of qualitative assessment and is treated as a brazing incompatibility, which disqualifies the possibility of using such heat exchangers in further stages of the manufacturing process. As mentioned above, erosion is mainly caused by the flow of liquid filler metal over the surfaces to be joined. In the literature there is a second theory of the formation of "erosion effect" being a result of the filler metal flowing out from the area where the phenomenon of dissolution of the core material has had already occurred [22].

From the viewpoint of durability and strength of the heat exchanger, the difference for the above-described terms are very important, because they cause creation of different singularities

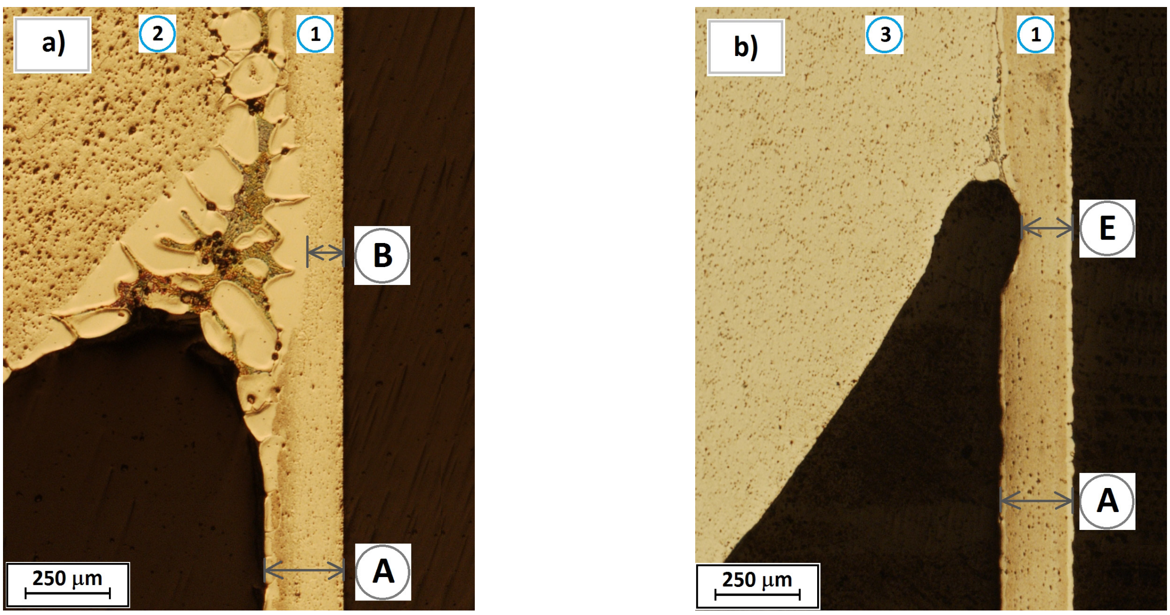

Fig. 4. Example of brazed joints of heat exchangers showing dissolution (a) – filler metal AlSi 7.5 and erosion (b) – filler metal AlSi 7.5 phenomena. Designation of aluminium alloys: (1) AlMn1Cu, (2) AlMn1Mg0.5, (3) AlMn1

of brazing incompatibilities. For cases where erosion occurs, reduction of wall thickness of the core material is present, this may cause cracks due to violent and / or long-term changes in temperature and / or pressure of the substances (both cooling and cooled) in the operation of the heat exchanger [11]. In the case of dissolution of the core material of heat exchanger elements occurred, even when the dimensional requirements for the joint geometry are met, this does not mean that such exchanger still may not get damaged. Due to the changed structure of the joint, its resistance to changing environmental conditions may change, e.g. it may be a place of attack of electrochemical corrosion.

The most frequently mentioned factors in the literature, that have impact on the occurrence of dissolution and erosion phenomena, are: too high maximum temperature which the heat exchanger reaches during brazing, and an excessive amount of filler metal located near the brazed joint [15,19]. Another factor is too long holding time at braze temperature in the furnace [17].

For the production of aluminium heat exchangers brazed in CAB technology, three types of filler metal are used (Table 1):

– the most commonly used EN AW-4343 (AlSi7.5, high-melting), has the widest range of brazing temperatures,
– EN AW-4045 (AlSi10, moderate-melting),
– EN AW-4047A (AlSi12, low-melting).

AlSi brazing filler metal with Zn addition has been recently used in the brazing of aluminum heat exchangers. However, such addition, depending on the amount of Zn, has the effect of lowering the melting point of the brazing filler alloy. This has a direct impact on increasing the brazing filler metal fluidity as a function of temperature. As a result, this can lead to an increased probability of erosion during brazing.

In the scientific and industrial community, for brazing aluminium, both terms dissolution and erosion of the core material are used. However, they have a completely different meaning. To facilitate understanding of the differences between the two phenomena, they are listed in Table 2, both in scientific and industrial terms.

3. Results and discussion

The occurrence of dissolution and erosion phenomena is presented by the example of a heat exchanger from the engine cooling system. Figure 5 shows an example of a radiator used in the cooling system of combustion engine, while Table 3 presents the data of the materials used for its construction.

Brazing tests of the radiator were carried out under serial manufacturing (industrial) conditions with the use of a continuous tunnel furnace, in an atmosphere of nitrogen with a purity of 5.0 (99.999%). The filler metal (cladded surface) was covered with NOCOLOK flux, applied using the electrostatic painting method, i.e. by spraying a mixture of air and electrostatically charged NOCOLOK flux particles [4,20]. Three different brazing

TABLE 1

Melting range and recommended range of brazing temperature of filler metals used for aluminium heat exchangers [23]

Filler metal designation (abbreviated as chemical symbols)	Nominal content of silicon [wt. %]	Temperature solidus-liquidus [°C]	Recommended range of brazing temperature [°C]
EN AW – 4343 (AlSi7.5)	7.5	577-613	593-621
EN AW – 4045 (AlSi10)	10.0	577-591	588-604
EN AW – 4047 (AlSi12)	12.0	577-582	582-600

TABLE 2

Description and interpretation of dissolution and erosion phenomena in both scientific and industrial terms

Term	Scientific description	Industrial interpretation
Dissolution of the core material	– static process, – result of diffusion processes; the liquid brazing filler metal interacts with the core material, – no change in the geometry of the brazed joint; changes in the structure of the brazed joint, – may affect the corrosion resistance of the brazed joint (heat exchanger)	describes the effect of the dissolution phenomenon in a quantitative manner, as a relative value of the thickness reduction of the core material, while maintaining the joint geometry (the thinned area of the core material is filled) – see equation (1)
Erosion of the core material	– dynamic process, – result of the flow of the liquid brazing filler metal, which interacts with the core material, – change in the geometry of the brazed joint (wall thickness reduction) as a result of eroding (rinsing out) of the core material, – affect the resistance of the brazed joint to changes in pressure and temperature of the cooled / cooling medium as well as corrosion resistance (heat exchanger)	describes the effect quantitatively, as a relative value of the thickness reduction of the core material, while the joint geometry is not maintained (thinned area of the core material is not filled) – see equation (2)

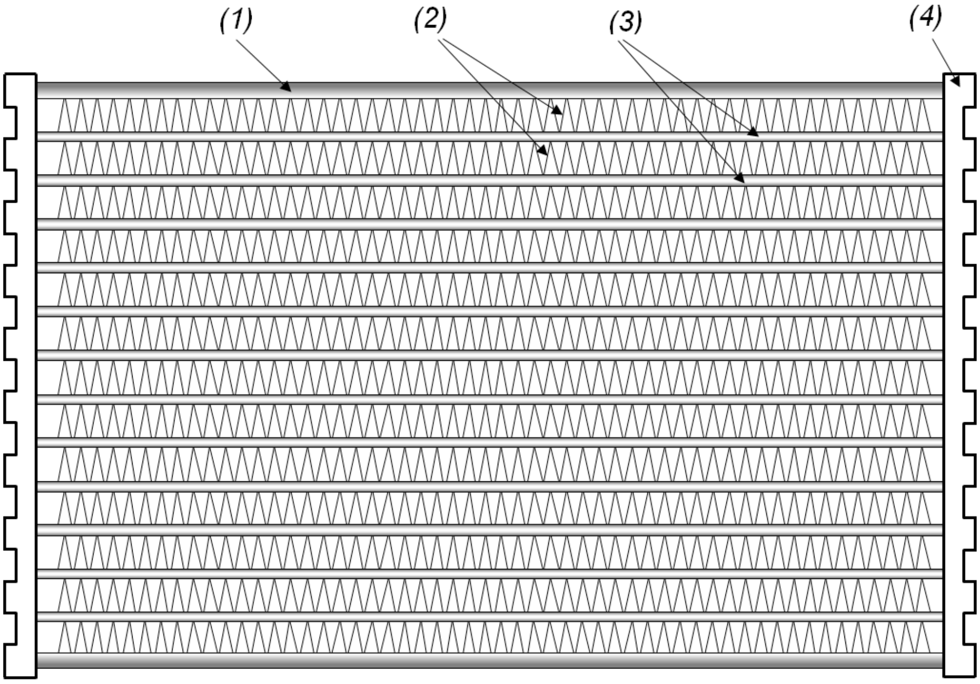

Fig. 5. Diagram of an example radiator heat exchanger: side-plate (1), fin (2), tube (3), header plate (4)

TABLE 3

Characteristics of materials used in the construction of an example radiator

Name of the element	Type of core material	Number of layers of material	Material thickness [µm]	Type of filler metal	Nominal thickness of filler metal [µm]
Side-plate	EN AW-3003	2	1490	EN AW-4343	74.5
Fin	EN AW-3003 + 1.5%Zn	1	75	No filler metal	0
Tube	EN AW-3005	3	250	EN AW-4343	36
Header plate	EN AW-3003	2	1490	EN AW-4343	74.5

temperature profiles were used (Fig. 6 and Table 4). Initially, the exchanger was brazed with a normal brazing profile, obtaining the maximum temperature and brazing time in accordance with the recommendations of the NOCOLOK flux manufacturer [4]. Then brazing was carried out using a hot brazing profile where both the time and the maximum temperature are slightly above the recommended maximum values. The last brazing test for this radiator was done based on a very hot brazing profile. In

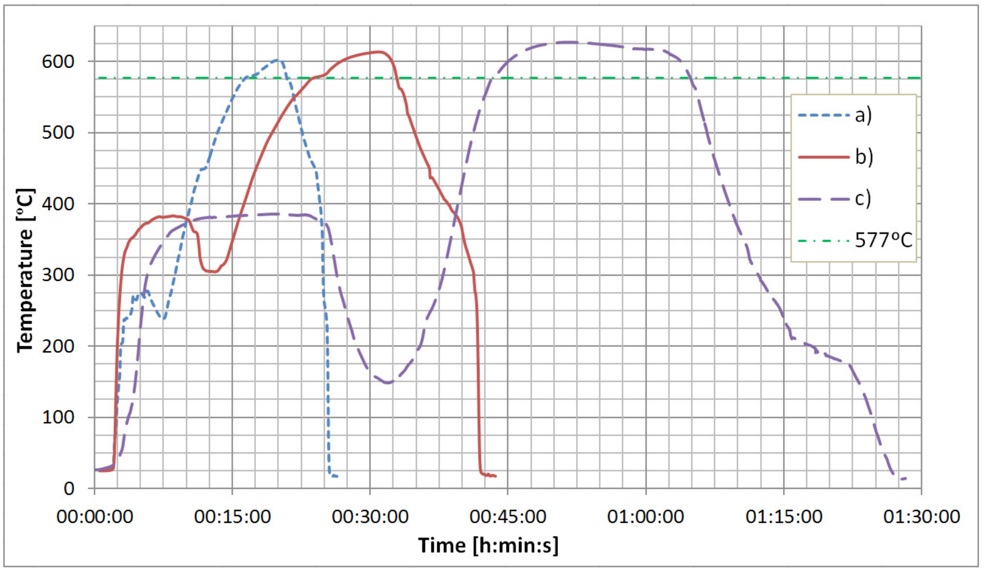

Fig. 6. Radiator brazing temperature profiles: normal profile (a), hot profile (b), very hot profile (c)

this case brazing time and maximum temperature significantly exceeded the recommended range, approaching the melting temperature of the core material. Both hot and very hot brazing profiles are not normally used for brazing of such radiators. They were used for research purposes to evaluate the effect of increased maximum brazing temperature and time on dissolution and erosion phenomena.

TABLE 4

Values of parameters obtained during brazing for an example radiator

Type of brazing profile	**Maximum temperature [°C]**	**Holding time above temperature 577°C [min]**
Normal	600-605	04:15-05:19
Hot	613-617	09:02-10:44
Very hot	626-627	20:15-22:01

Figure 7a-c shows the brazed joints of radiator in the following system: tube – fin – side-plate, for three temperature profiles of brazing.

For a normal brazing profile, the exchanger obtained the maximum temperature in the range of 600-605ºC, with EN AW 4343 (AlSi7.5) filler metal used, with a melting point of 577-613ºC. However, for both the hot and very hot profile, the maximum brazing temperatures obtained exceed the liquidus temperature of the filler metal used. As a result, the total liquid state of the filler metal is obtained and the intensification of dissolution and erosion phenomena is increased.

In Figures 7a-c can be noticed a clear effect of a larger amount of filler metal on the side-plate (upper element) in relation to the quantity of filler metal on the tube (lower elements). Even for a normal (cool) temperature profile, the size of the brazed joint (filling of gap) and the dissolution of the side-plate (1) and fin (2) in this area are greater than for the elements in the lower joints (tube to fin joints). In case of a hot brazing profile, the phenomenon of fin erosion can be seen from the side-plate side, while from the tube side the joint looks correct. However, for a very hot brazing profile, erosion occurred on both sides of the fin, but it was mainly due to the migration of the filler metal from the side-plate and some fin waves disappeared completely. Dissolved by the liquid filler metal. In addition, on Figure 9a-c can be seen, that for the connection of the tube (3) with the fin (2), erosion phenomenon has not occurred. This was independent of the temperature profile. However, both hot profiles have shown significant dissolution of the brazed materials.

Figure 8 shows a detail of Figure 7a. This shows the dissolution of the fin brazed on the normal brazing temperature profile. The dissolution value for the marked place in this case is approximately 66% (based on Formula 1). This is a significant reduction as it does not fit in the majority of acceptable requirements or recommendations.

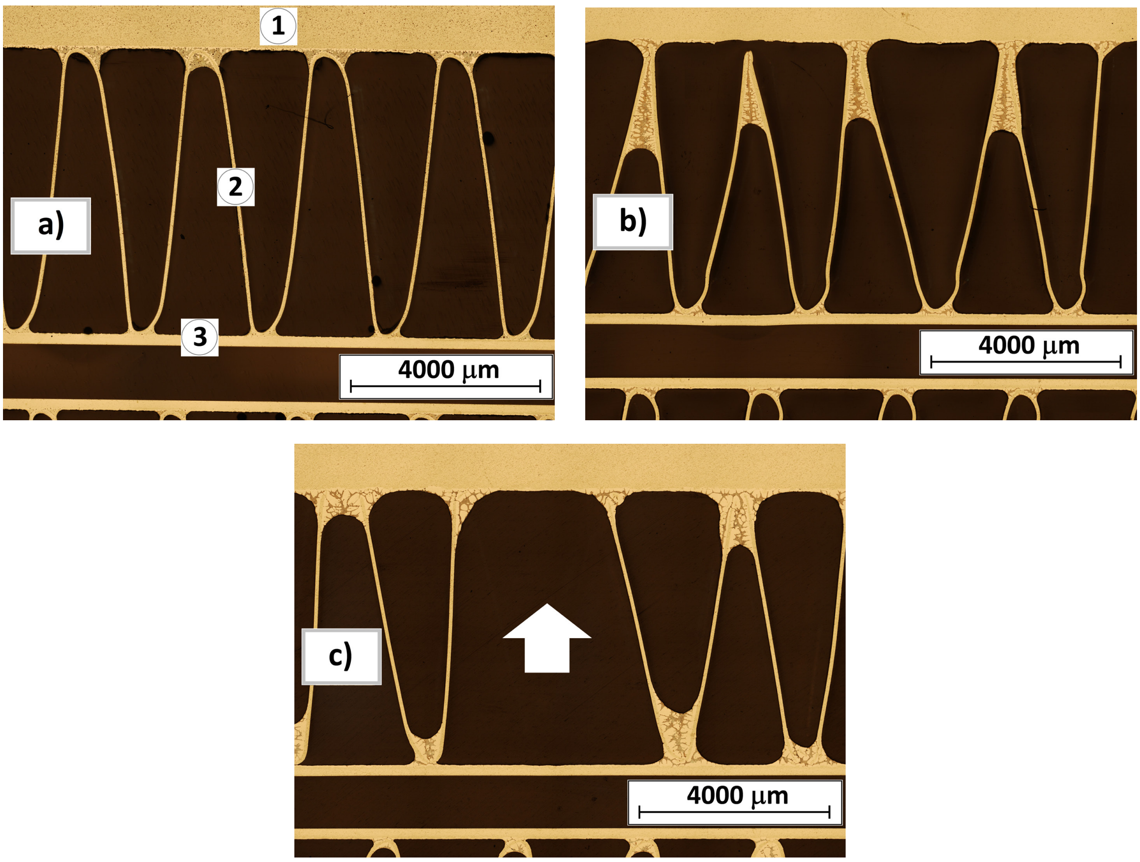

Fig. 7. Brazed joints of the heat exchanger for the connection of the tube – fin – side-plate, in the radiator, for three temperature profiles of brazing: normal (a), hot (b), very hot (c), the arrow indicates the complete erosion of the fin ; Component designation: side-plate (1) – filler metal AlSi7.5; fin (2) – no filler metal; tube (3) – filler metal AlSi7.5

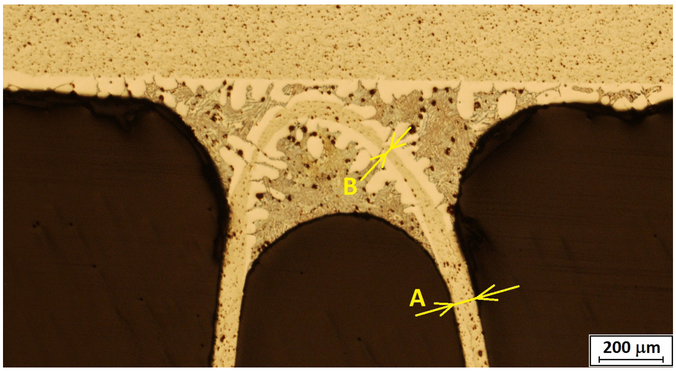

Fig. 8. Dissolution the fin core material, for a normal brazing temperature profile (detail from Figure 7a)

Interestingly, for a very hot brazing profile, the average size of the brazed joint between the fin and the tube is much smaller than for the hot profile (Fig. 9). This may be due to the deterioration of the wettability of the surfaces of both materials and it is caused by partial evaporation of the flux applied before brazing due to the prolonged brazing time.

Figure 10 shows cross-sections of the tube and header plate joint, where with the maximum temperature and brazing time increase, the structure of the joint (filled gap) changes and the dissolution value of both elements also increases. Table 5 shows the absolute values of the material dissolution of the tube and header plate. By analyzing these values, it can be seen that for the same brazing profile, the dissolution value of the header plate

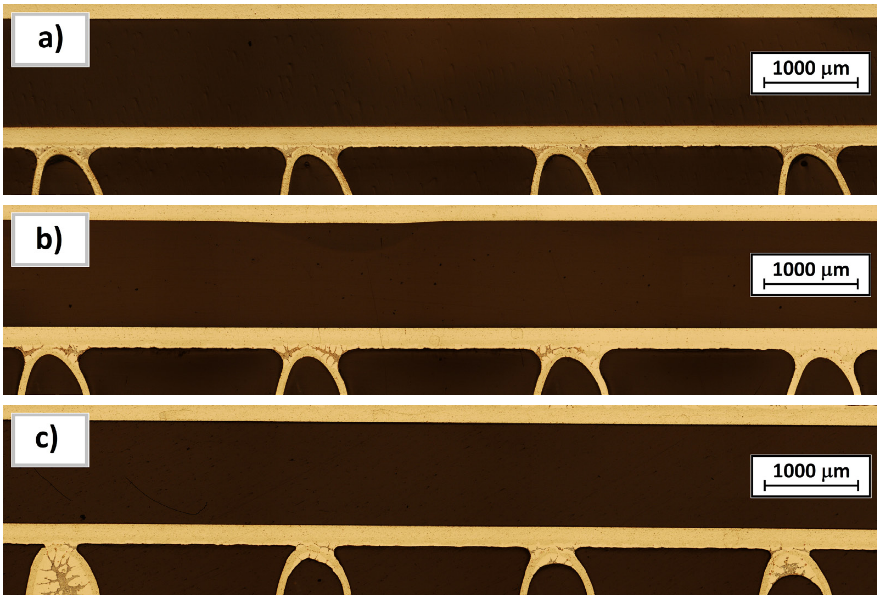

Fig. 9. Comparison of the brazed joint size between the tube and the fin (enlargement of Figure 7) for the 3 brazing temperature profiles: normal (a), hot (b), very hot (c)

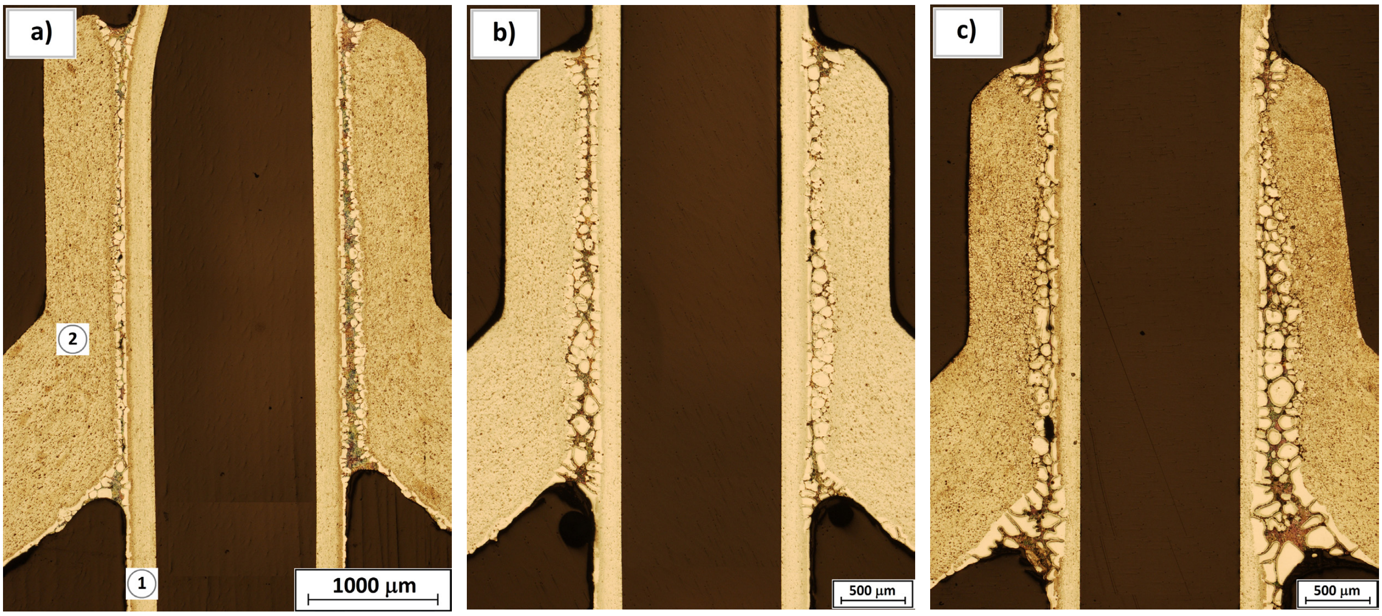

Fig. 10. Macrostructure of brazed joints of heat exchangers for the connection between tube and header plate in the radiator, for three temperature profiles of brazing: normal (a), hot (b), very hot (c), elements marking: tube (1), header plate (2), filler metals AlSi7.5

TABLE 5

Dissolution values of tube and header plate material for the individual brazing profiles

Type of brazing profile	Dissolution value of header plate [μm]	Dissolution value of tube [μm]	Dissolution value of tube [%]
Normal	130	40	18
Hot	191	83	38
Very hot	262	151	68

material is always much greater than that of the tube material. This may be due to the difference in grain growth of the core material of the tube and header plate during brazing.

4. Conclusions

- The influence of too hot liquid filler metal on brazed elements of aluminium heat exchangers clearly shows the danger of the phenomena of dissolution and erosion. These in effect is "devour" the brazed materials.
- Analyzing examples of brazed joints obtained from the production of heat exchangers, one of the main causes of the erosion phenomenon was too much filler metal (in the form of clad) used to make a given joint. This was observed in all the examples.
- Based on the results obtained, it can be concluded that in the place where the amount of filler metal was appropriate, no erosion was observed, despite the increase in both the time and the maximum brazing temperature.
- With an increase of maximum temperature and brazing time, the intensification of the dissolution of the brazed elements increases. The maximum relative values for the dissolution of the tube (based on Formula 1) vary from 18 to 68% depending on the brazing profile used. This dissolution may have a negative effect on the life of the heat exchanger during its operation.
- A recommended normal brazing profile should be used to reduce the adverse effects of dissolution and erosion phenomena. However, in some cases even this may not be sufficient to prevent erosion or significant dissolution phenomena from occurring. This can take place for example, when the type of filler metal is incorrectly selected or its amount is too great.
- The correct selection of the type and amount of brazing filler metal at the design stage, limits the possibility of excessive dissolution of the core material or its erosion in industrial brazing process. Preliminary brazing tests are required to determine the suitability of the selected brazing filler alloy.

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