Diffusion Bonding Technique Concerning Production of Microchannel Heat Exchangers

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***Abstract* — Diffusion bonding process of aluminium 1070A concerning production of microchannel heat exchangers (MCHE) has been investigated. It has been proposed to raise manufacturability of the process owing to introduction into contact zone of joining details composition on the basis of sodium silicate before welding. The results of investigations of microstructure and chemical composition of welded joints and also mechanical strength of products have been presented.**

Keywords — aluminium; microchannel heat exchanger; diffusion vacuum welding; oxide film; surface activation; welded joint; mechanical strengh

I. Introduction

Recently for refrigeration of electronic devices, particularly in large offices and data centres, using of water cooling systems becomes reasonable and economically sound. Such systems allow to enhance the reliability of attached equipment (computers, servers, network devices) in wide range of temperatures, reach the noise abatement in workrooms, facilitate the work of conditioning systems.

Water cooling permits refuse productive ventilators in computers and servers entirely or ventilators in office and server premises at all. Such big complexes enable to utilize double-loop systems with high-performance heat exchangers or cooling systems in secondary loop, which are placed into separate premises with good sound insulation (cold stores, chillers) [1-5].

As heat exchangers in water cooling systems, destined for refrigeration a large number of electronic devices, microchannel heat exchangers (MCHE) wholly fabricated from aluminium are widespread lately [1-5] (Fig. 1).

Such heat exchangers are more durable, compact, power efficient and reliable in operation as opposed to conventional ones. These advantages are achieved due to structural specifics of MCHE [5]. Firstly, they consist of plates with microchannels, which promote increase of total inner surface area, and ribbing of special shape attached to them. Secondly, collectors with partition walls ensure the most effective distribution of cooling agent through microchannels. And thirdly, owing to high corrosion resistance of aluminium, the risk of galvanic corrosion initiation is fully excepted, while in conventional heat exchangers it is impossible to avoid corrosion due to galvanic currents flow during contact of two metals (copper and aluminium).

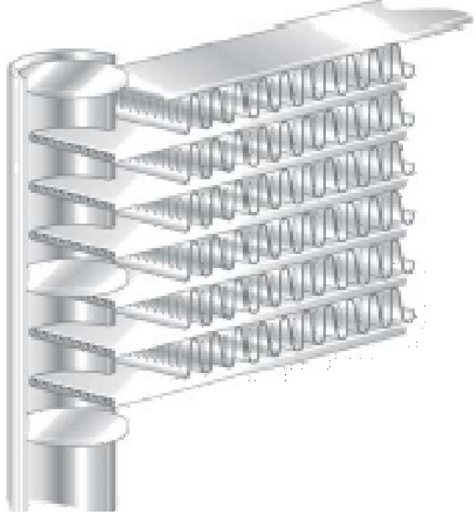

Fig. 1. MCHE structure, Danfoss Company [5]

The complicated construction and large dimensions of heat exchangers require searching and using of the most technological method of their production and receiving qualitative permanent joint of their typical units. It is necessary to assure high strength and design shape keeping of such products, especially joints of microchannel plates and irregular shaped ribbed elements.

II. Problem Statement

The formation of qualitative joints of aluminium is impeded by high-melting oxide film Al_2O_3 (melting point is 2050 ^{0}C). It arises instantly on surface of aluminium when it contacts with the air and has strong cohesion with the metal surface. Oxide film removal before joining without sophisticated technologies doesn't ensure physical contact of details.

Flux brazing of such products must provide deposition of flux and placing of braze. At the same time it is necessary to dose braze amount since surplus of braze results in its running-off. Besides beads appear in which brazed metal dissolves with the formation of undercuts.

The work practice shows that when brazing aluminium and alloys, especially in large-scale and mass manufacture, braze

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is placed by metal cladding. However, this isn't providing guarantee manufacturability [6].

Brazing in flux bathes of large-size products needs a big amount of flux. In a number of cases besides solution of brazed metal the erosion also occurs in melted flux. The last has bigger negative effect on brazing process and receiving qualitative brazed joints.

The manufacturability increase of brazing process is achieved by using reactive-flux soldering, when solder forms owing to metal reduction from flux or dissociation of one of its components [7]. But such method is characterized by all drawbacks of soldering: low strength of soldered joints and low corrosion resistance.

For brazing of aluminium and alloys silumins are mostly used due to their high flowing (mainly eutectic silumin AlSi12) and also braze 34A, which allow receiving sufficiently strength and inoxidizable joints. Copper contained in braze 34A facilitates decrease of its melting point but along plasticity reduces and brittleness grows simultaneously. At the same time problem of galvanic corrosion initiation appears again. Silumins in their turn are corrosion-resistant in damp atmosphere and sea water, in weak acid and alkaline mediums.

Diffusion vacuum welding through interlayer of mentioned products opens more opportunities. Using of vacuum atmosphere minimizes factors prevented diffusion process. The process manufacturability could be raised by ensuring some requirements: no need of careful preparation of details to welding, create conditions for effective transportation of silicon containing medium to pure aluminium under oxide film.

III. Choice of Solution Methods and Approaches of Given Problem

It is known that during contact with silicon activation process can become slower through high stability of its oxide. Due to weak evaporation of silicon in vacuum $1.33\cdot10^{-2}$ Pa at eutectic melting points the tight clamping is needed for contact of aluminium with silicon through discontinuities in film Al_2O_3 [7].

The effective method which ensures both physical contact and diffusion passing is the forced straining of materials in joining zone [8]. Under plastic strain there are mechanical destructions of oxide films on joined surfaces, thus the contact surface area increases and plastic straining of near-contact zone occurs. All this factors activate diffusion processes in junction. However since deformation level of base material is large this method is limited in use, especially for production of thin-walled structures.

Impulse deformation, which ensures intensive mass transfer through contact zone [9], also can't solve current problem as we supposed.

The intensification technique of volume interaction zone formation during diffusion vacuum welding of metals is offered in [10], [11]. The interlayer in this case isn't placed directly on metal surface, but forms during process of sublimation of some metal pairs under autovacuum conditions. This method enables us to propose the use of interlayers with defined composition for joining aluminium. Such interlayers permit to receive necessary reagents during heating in vacuum for faster formation of liquid low-melt eutectic Al-Si, oxide film dispersion and its removal from joining zone [12], [13].

Essence of development is defined by next considerations. Silicon contained in silumins segregates as rough needle-shaped crystals under eutectic solidification. These crystals have a role of cuts in plastic aluminium [14]. For structure refining and removal of redundant crystals silumins are modified by sodium, namely by mixture of salts 67% NaF + 33% NaCl. In the presence of sodium displacement of phase diagram occurs (see Fig. 2) and hypereutectic alloy AlSi12 becomes hypoeutectic one. Eutectic acquires more fine structure and consists of fine silicon crystals and α-structure. This is caused by that during solidification process the film of sodium silicide obduces silicon crystals thus impeding their growth. Such changes improve mechanical properties of aluminium.

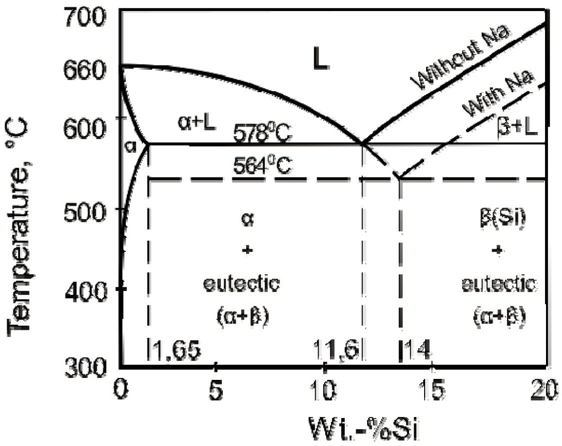

Fig. 2. Al-Si phase diagram [14]

Phase diagram Al-Na is characterized by very slight solubility of elements in each other both in liquid and solid state [15]. The solubility of Na in liquid Al increases from 0.1 wt-% at temperature 700 ^{0}C to 0.13 wt-% at temperature 800 ^{0}C. Aluminium at solid state doesn't dissolve in sodium practically or dissolves insignificantly: 0.003 wt-% at temperature 659 ^{0}C and about 0.002% at temperature 550-650 ^{0}C.

Phase diagram Na-Si isn't built. Series of compounds Na_xSi_y generate. Silicon doesn't dissolve in sodium virtually (solubility of silicon in sodium at temperature 650 ^{0}C is $2.4\cdot10^{-3}$ amu-%) [16].

Hypoeutectic alloys AlSi12 and AlSi10Mg additionally doped by magnesium can be hardened besides modification by means of heat treatment. Strengthening phase is magnesium silicide Mg_2Si [12].

Researches showed [7] that, when brazing on silumin type braze with content of more than 2% of magnesium, the dense oxide film MgO appears on braze before and during its fusion. It is the result of magnesium oxidation and its interaction with the rest of oxygen in evacuated environment. Wetting of alloy

AlMn1 by brazes with 5-10% of Mg occurs only under heating to 630 ^{0}C, probably due to high density and thickness of film MgO. Therefore the introduction more than 2% of Mg to braze 34A and silumin is unfavourably.

Authors [7] indicate that significance of magnesium is mainly come to cleansing the vacuum atmosphere of furnace and reduction of aluminium from oxide film. But it is known that there are two eutectics in the system Al-Mg-Si: one enriched with silicon and with melting temperature 550 ^{0}C and one enriched with magnesium and with melting temperature 450 ^{0}C. The melting temperature of binary eutectic Al-Si is 577 ^{0}C. Thus the possibility of aluminium brazing by silumin in magnesium vapors confirms the presence of contact solid-gas melting.

Therefore from the above it follows that when brazing of aluminium and alloys by silumins it is necessary to ensure introduction of sodium and magnesium to contact zone.

According to one of theories oxide film is removed owing to the formation of caustic soda during brazing by interaction of its chloride with the rest moisture. Consequently sodium aluminate soluble in water and flux forms [6]:

$$Al_2O_3 + 2NaOH \rightarrow 2NaAlO_2 + H_2O \cdot$$

As indicated in [6] the presence of moisture always contained in flux and on surface of brazing details contributes to fluxing of aluminium surface. The moisture is introduced with the product since it is present on surface of details invariably. The heating of products up to 530 ^{0}C reduces the amount of moisture on surfaces but doesn't except it entirely. So the moisture is in joining zone anyway.

IV. MATERIALS, METHODS AND RESULTS

The experiments were carried out on samples of aluminium 1070A with dimensions 8×8×10 mm. Surface preparation was consisted in scraping the near-contact layer by thickness 0.2-0.3 mm and in following degreasing. On basis of above-mentioned considerations the composition Na_2SiO_3-HCl-Mg was used as interlayer.

The proportion of components is determined by the amount of silicon which contains in mixture and participates in the formation of eutectic alloy Al-Si (88.3 wt-% of aluminium and 11.7 wt-% of silicon). Towards its mass magnesium is introduced in quantity ≤ 1.5%. The presence of last in mixture makes possible the direct reduction of the oxide film Al_2O_3 by magnesium vapours with the formation hardened phase Mg_2Si. Silicon precipitates owing to passing of chemical reactions mentioned below:

$$Na_2SiO_3 + 2HCl \rightarrow H_2Si_2O_3 + 2NaCl;$$

$$12\,Na_2SiO_3 + 6H_2O \rightarrow 6Na_2Si_2O_5 + 12\,NaOH\ ;$$

$$Na_2Si_2O_5 + Al_2O_3 + 8Mg \rightarrow 2Al + Si + Na_2Si + 8MgO;$$

$$H_2SiO_3 \rightarrow SiO_2 + H_2O;$$

$$Al_2O_3 + 2NaOH \rightarrow 2NaAlO_2 \downarrow + H_2O;$$

$$SiO_2 + 2Mg \rightarrow 2MgO + Si;$$

$$Si + 2Mg \rightarrow Mg_2Si;$$

$$Mg_2Si + 4HCl \rightarrow 2MgCl_2 + SiH_4 \uparrow .$$

Particularly one of the intensifying factors is the formation of monosilane SiH_4 which possesses enhanced reductive properties.

Technological process of bonding concludes precleaning, rough mechanical scraping and degreasing of joining surfaces, following putting the composition on one of them, assembly of details and their fixation in heater of vacuum furnace. After that creating of the rarefaction $10^{-2} \div 10^{-3}$ Pa, heating to the temperature 580 ^{0}C, applying of the specific pressure 0.1 MPa, isothermal soaking over a period 900 sec, cooling and pulling-out of product from furnace follow.

Microsections for metallographic researches were made by standard procedure with using of diamond pastes. The etching of samples was carried out in mixture of hydrofluoric and nitric acids (2:1 volume fractions). The chemical composition of welding zone and surrounding metal parts was determined by micro-X-ray analysis with the help of raster electron microscope JSM-840 of company "JEOL".

By scanning electron microscopy method it was determined that eutectic mixture fills the gap in joint and ensures qualitative formation of welded zone (Fig. 3).

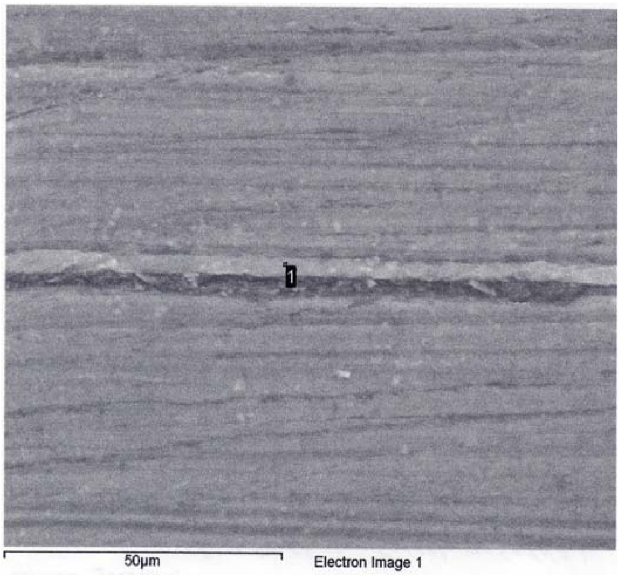

Fig. 3. View of welded joint

According to data of micro-X-ray analysis the concentration of elements directly in weld seam (point 1 at Fig. 3) makes 87.65 wt-%Al – 10.87 wt-%Si – 1.28 wt-%Mg –0.2 wt-%Na.

At bigger microscope magnification crystallized metal interlayer was discovered in welded zone (see Fig. 4). Under given thermodeformative conditions welded seam forms due to splicing of crystals and transition zones. Practically full pressing-out of liquid phase from welded joint was indicated (Fig. 5).

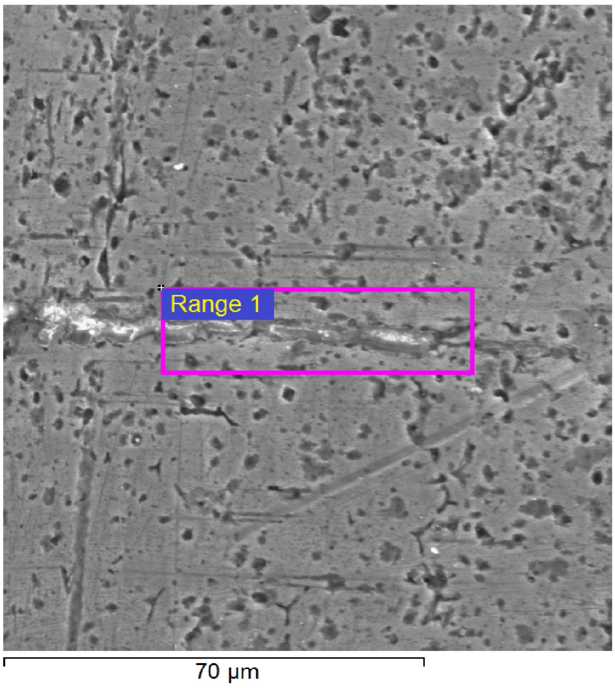

Fig. 4. Metal interlayer in welded joint

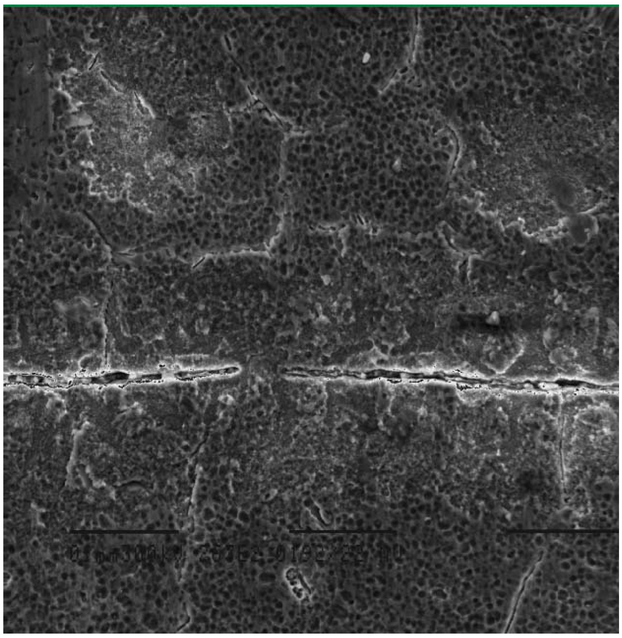

Fig. 5. Pulling-out of liquid phase in welded joint

At this stage of investigations shear strength of welded joints reachs 51 MPa which is 82% from strength of base material.

V. Conclusions

The new method of chemical activation of aluminium surface in pressure welding was developed. It was determined that introduction of interlayer on the basis of composition Na_2SiO_3-HCl-Mg into contact zone of details before diffusion vacuum welding allows to receive welded joint through eutectic alloy Al-Si. Owing to using of interlayer of proposed composition the volume of preparatory works before welding decreases. Due to adhesion properties of compound put on by pasting of the details assembly of item is simplified. Therefore manufacturability of welding process increases. The technology developed allows getting welded joints of aluminium details with shear strength 51 MPa which is 82% from strength of base material. The actual task of investigations in production of heat exchangers is the development of bonding technologies of aluminium which could be able to ensure the effective removal of oxide film in a short time. It is especially important for getting precision joints of electronic devices.

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