Optimization of Induction Brazing for Thin-Walled Aluminum Tubes

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Abstract: - Major environmental concerns have triggered lately some important developments in applicative research. Innovation programs for manufacturing industry are intended to achieve both lower emissions of carbon dioxide and smaller specific energy consumption. Since use of inductive brazing for aluminum has remained restricted to few applications, a complex research program has been pursued in order to develop an optimized joining technology for tubes with thin walls. The new technology should be suitable for large scale production, to replace torch brazing at better costs and lower carbon dioxide emissions. An experimental study, which includes complete design of technology and equipment for inductive brazing, has proved that use of induction could produce high quality joints and eliminate the considerable scrap level generated by torch brazing. Induction brazing also lowers energy consumption and totally eliminates direct emission of carbon dioxide.

Key-Words: - Emission-free technology, Induction brazing, Thin-wall aluminum tubes, Reduced energy consumption.

1 Introduction

Industrial activities are lately influenced by considerable efforts for innovation and applicative research, focused on both lower energetic consumption and reduction of greenhouse gas (GHG) emissions. The main reason for these developments is public concern produced worldwide by estimated anthropogenic global warming of lower atmosphere. As a consequence, numerous legal regulations have pushed industrial companies to optimization of existing processes and introduction of more environment-friendly processing technologies, which are intended to reduce greenhouse gas emissions.

For example the targets imposed by Kyoto agreement, as well as the "–20 percent" target for emission reduction until 2020, imposed by the European Union, have triggered a large number of technical and managerial improvements.

The greenhouse effect, considered responsible for global warming, is produced mostly by gases that enter the atmosphere because of human activities. The most important are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and some fluorinated gases (hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, etc.) Approximately 80% of total emissions in the European Union are energy-related. Most greenhouse gas emissions result during production of electricity or heat, road transportation, fossil fuel and combustion in manufacturing industries. Other major contributors are household, agriculture and steel industry. An estimation of the European Environment Agency (EEA) shows that carbon dioxide represented in 2007 a portion of about 83% of all greenhouse gas emissions responsible for climate changes [1].

Reducing production of carbon dioxide, which results mainly as product of fossil fuel burning, could be an important vector to eliminate harmful emissions. If clean energy is used for large scale industrial process, the final influence is highly enhanced [2].

Several methods may be considered for reduction of carbon dioxide emissions during industrial processes that imply burning of fossil fuel:

- Optimization of process parameters, which results in decreasing specific consumption of energy;
- Design of more stable technologies that could decrease the amount of scrap or waste;
- Better quality of products, which could extend the performances and durability;
- Evaluation of alternative technologies that do not imply burning of fossil fuel and direct carbon dioxide emissions. In this respect, applying various methods of electric heating could have an important virtual effect.

Although production of electric energy is in many cases based on fossil sources (coal, gas, oil), it may be assumed that power plants have better efficiency and could more easily adopt environment-friendly measures and technologies. Virtually all improvements implemented for electricity production will propagate their positive effect to all industrial processes that use electric energy instead of burning fossil fuel.

2 Torch brazing of aluminum tubes

Aluminum alloys have become lately a major choice for components where high mechanical properties should meet low specific weight, especially automotive industry, aeronautics, household equipment etc. [3, 4]. Another important reason for extension of aluminum use is the exceptional ability of recycling and that recovered aluminum consumes only 10 percent of energy needed to produce a new one.

The present research has been focused on optimization for fabrication of large assemblies composed of aluminum tubes with thin walls, largely used for circulating fluids in heating and air conditioning systems of automobiles.

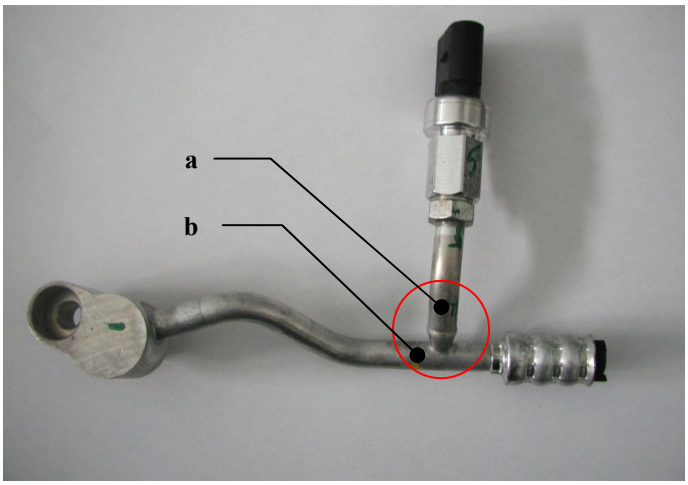


Fig. 1. Appearance of brazed assembly with thin wall components: a - vertical tube; b – horizontal tube.

An example of such an assembly is illustrated in figure 1. Two aluminum tubes with wall thickness of 1,5 mm have to be joined at a 90 degree angle between axes. The joint has to be perfectly tight and to resist mechanical forces that are involved in exploitation or during car assembling.

The present solution for large-scale assembling of the aluminum tubes is based on torch brazing. Tubes are heated together with a small ring of aluminum –silicon alloy, which provides the brazing filler. Brazing components are shown in figure 2.

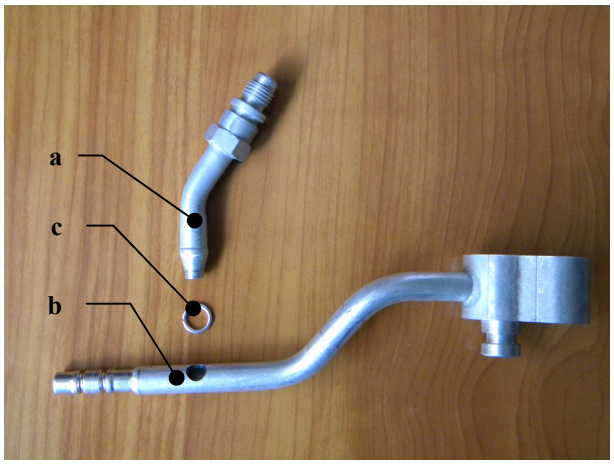


Fig. 2. Components used for fabrication of assembly: a - vertical tube; b – horizontal tube; c – brazing filler.

The torch brazing setup is presented in figure 3, and is composed of a positioning device, made of thermo-resistant steel, and two torches for each heating cell.

Total time necessary for completing one cycle of brazing (two preheating phases and one final heating) is of 60 seconds. During this cycle the tubes move from one cell to another on a rotating table.

Torch brazing is still the most common method used for industrial applications, since the technology requires only simple equipment and brief personal training. However torch brazing has proved to have serious limitations that require optimization for both economical and technical reasons. There are a number of problems that are connected with the use of flame for heating and have to be overcome by alternative technologies, such as induction [5,6]:

- The flame has a very high temperature and could easily produce overheating of the joint area and structural flaws, such as accelerated corrosion, melting of grain limits and increase of grain size. Therefore the joint become fragile and lose leak tightness. Grain size increase is enhanced by the fact that in some cases the material could be plastically deformed at higher ratio near the joining area;

- There are many factors influencing flame shape and temperature, such as pressure, flowing rate and purity of the combustive gas, presence of air currents, shape and position of burners, etc. All of these represent possible causes for process instability and higher scrap level, which could frequently rise up to 10%;
- The heating is normally localized on small material spots, which are in contact with the flame. This fact causes an initial non-uniform distribution of temperature, which requires pre-heating and equalization pauses between heating phases. The result will be a longer brazing cycle and an increase in energy consumption;
- Generation of flame is based on burning of gaseous hydrocarbons, usually propane, an environment unfriendly solution, with considerable emission of carbon dioxide [7].

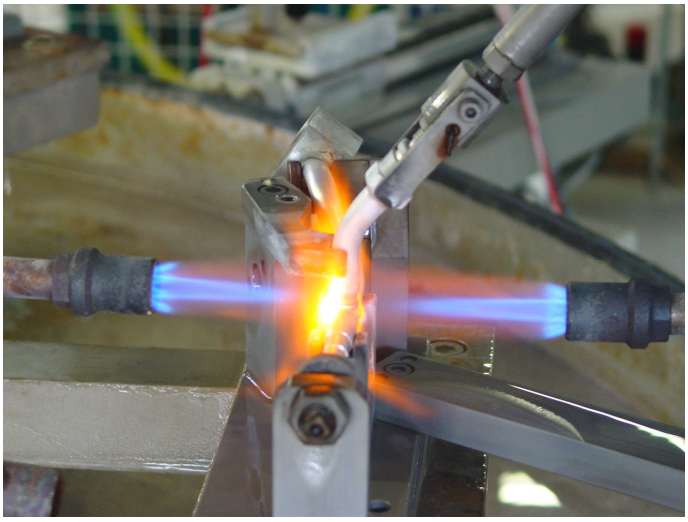


Fig. 3. Torch brazing of tube assembly.

3 Advantages of induction heating

Induction heating of metals is used for many decades in large scale industrial processing, such as surface hardening, brazing, forging, etc. Some difficulties in controlling the complex phenomena that are involved (electromagnetic induction, pellicular effect of alternative current, thermal effect of eddy currents etc.) have limited the extension of induction heating and many users have preferred more simple approach based on flame heating.

The increasing public concern for environmental effects of industrial activity has lately renewed the interest for induction, especially to replace flame heating, based on burning of liquid or gaseous hydrocarbons. Although inductive hardening already has an extensive use, and has become one of the predominant surface treatments, assembling by brazing is still based on torch heating.

Induction has some important advantages for heating in industrial processing, especially in comparison with flame heating:

- Heat is generated inside the metallic part, without any contact between tool and part, which increases both rate and efficiency of energy transfer;
- Induction is considered among the methods, which assures a high energetic density; therefore very high temperature levels could be achieved within short heating periods of time;
- Since heating time is considerably reduced, there are large possibility for high fabrication efficiency. On the other hand the material is not exposed to oxidation or decarburization and practically any processing atmosphere could be adopted;
- Physical characteristics of induction allow selecting precisely the depth and surface of heated material; therefore heating is closely targeted and thermal losses are minimized, which could produce significant energetic savings;
- Heating is controlled by electrical parameters, which permits a very precise control, good process reproducibility and practically no influence from environmental conditions (humidity, air currents, temperature, etc). Another consequence of the electrical control of the process is that heating may be easily automated and programmed;
- Unlike other heating methods that are used in industry, such as flame heating, there is no environment pollution. Latest concerns related to carbon dioxide emissions, which has become a major issue in accelerated economical development, are expected to promote larger scale use of clean heating methods;

Economical and environment benefits are even more emphasized when large scale production is concerned. This is the case of automotive industry, which frequently uses assembling techniques based on welding or brazing. Aluminum alloys represent a major choice for applications where lightweight has to be accompanied with high mechanical properties, corrosion resistance and efficient processing. This is the case of complex systems of modern cars used for fluids circulation. High processing efficiency can be achieved, when large assemblies of aluminum tubes can be easily produced by mean of brazing.

There are some important advantages of brazing for aluminum, which could be the reasons for increasing use in automotive industry:

- The brazing filler is also an aluminum alloy and will produce a joint with mechanical resistance comparable with the base material;
- The filler metal will form a meniscus surface that is ideally shaped, with no sharp edges, providing good fatigue properties;

- The processing temperature of aluminum brazing is relatively low, around 575°C, so the processing temperature can be generated within short time cycles. This means that aluminum brazing does not require any controlled atmosphere;
- Because processing temperature is lower than in the case of welding, energetic costs are inferior. If technological parameters are correct, structural changes in material are also reduced, conserving mechanical properties and corrosion resistance of the aluminum alloys [8, 9].
- Brazed joints represent a cost-effective solution because there is no need for any intermediary component and no additional machining is required.

4 Experiments and optimization

The present study belongs to a larger research program which intends to replace the torch brazing of aluminum tubes, largely used in automotive industry, with induction brazing, and to evaluate technical, economic and environmental advantages. Brazing induction technologies and experimental equipment have been developed for assembling several types of complex components.

4.1 Material characteristics

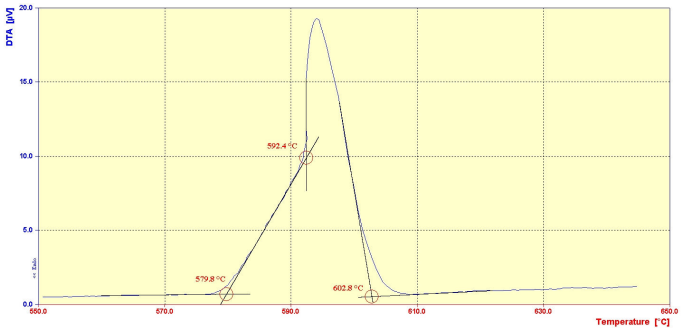
The systems used for circulating fluids in automobiles contain extruded tubes from alloys belonging to the aluminum - manganese (3000), aluminum -magnesium (5000) and aluminum –magnesium- silicon (6000) families. The reasons for such a choice is based on both mechanical and corrosion resistance.

The brazing filler is also an aluminum alloy, which has a melting temperature lower than the base material of the joint parts, having a near-eutectic concentration in the aluminum - silicon system. Therefore, the most sensitive technological problem is to provide a temperature distribution that allows melting of the filler, and does not produce melting or coarse grain size in base material.

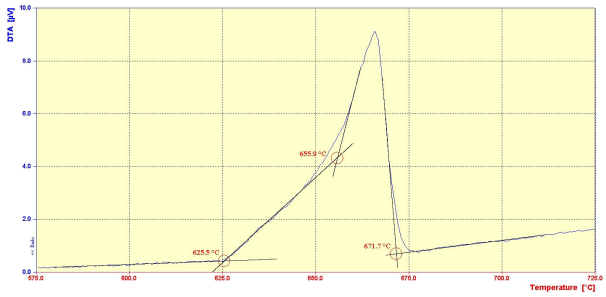
The optimization has been realized for brazing of a T-shaped assembly (figure 1). Both horizontal and vertical tubes are fabricated from the EN AW 3103 (AlMn1) alloy.

The brazing filler is shaped as a small ring of binary aluminum-silicon alloy Al 104 (L-AlSi12), with a near eutectic composition, since heating during brazing process should produce rapid liquefaction of filler, while base material remains in solid state.

Since temperature levels achieved at heating seem to be critical for the process, a separate study has been pursued to determine the solidus and liquidus points for both base material and metallic filler. Differential Thermal Analysis has been utilized for samples extracted from tubes and ring of filler.

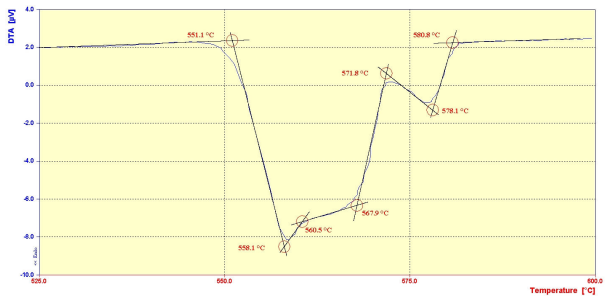


a) DTA heating curve of 3103 alloy.

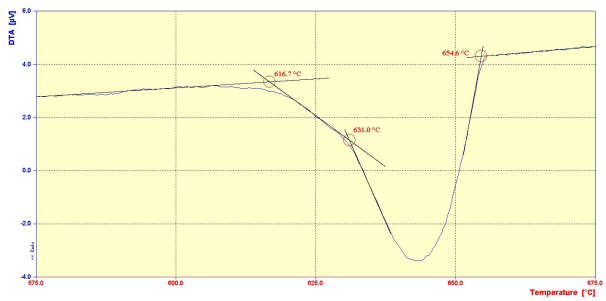


b) DTA heating curve of Al 104 alloy.

Figure 4. DTA heating curves of brazed components.



a) DTA cooling curve of 3103 alloy.



b) DTA cooling curve of Al 104 alloy.

Figure 5. DTA cooling curves of brazed components.

Samples have been heated and cooled in a Baehr DTA 703 equipment, up to 800°C in argon atmosphere, with a

rate of 10°C/minute. Resulting DTA curves for heating and cooling are presented in figures 4 and 5 respectively. Experimental values for critical point determined graphically on the DTA curves are shown by Table 1.
It may be concluded that during heating for brazing the Al 104 alloy, which represents the metallic filler, is completely melted at liquidus temperature of 602,8°C and the 3103 alloy of the tubes remains completely solid until 625,5°C. Therefore, there is a window of about 20°C which allows an optimal brazing, when melted filler being completely liquefied has a good infiltration and provides tightness to the joint, while tube material is still in solid state, providing optimal microstructure.

Table 1. Transformation points of aluminum alloys.

Analysis Phase	Alloy Designation	Solidus Point [°C]	Liquidus Point [°C]
Heating	3103	625,5	671,7
	Al 104	579,8	602,8
Cooling	3103	616,7	654,6
	Al 104	551,1	580,8

4.2 Brazing parameters

Apart from relatively close melting points of tube material and brazing filler, aluminum alloys have a high thermal conductivity, which makes relatively difficult to achieve a localized heating. Temperature distribution could be also influenced by external factors, such as air currents, contact with positioning devices, power variation of the heating source etc.
Therefore an optimization of inductive heating is crucial in order to consecrate such a technology.
In the case of aluminum, energy absorption is based on following electromagnetic effects:
- Alternating magnetic field generates eddy currents inside aluminum parts, and heating occurs due to electrical resistance of metallic material;
- Most of the eddy currents are localized on the superficial layer of the heated part, which is called skin or pellicular effect;
The depth of the layer which contains most of the induced currents is usually called *reference depth* and is strictly related to the frequency of alternating fields:

$$\delta = 1{,}6\sqrt{\frac{\rho}{f \cdot \mu}} \qquad (1)$$

In relation (1) there are following symbolizations:
- δ represents the reference depth in millimeters,
- ρ is the electrical resistivity in μΩ·cm;
- f is the frequency of inductive field in kHz, and
- μ represents the relative magnetic permeability of material in which the eddy currents are induced.

In the case o aluminum alloys the dependences is illustrated in logarithmic representation by the diagram in figure 6.

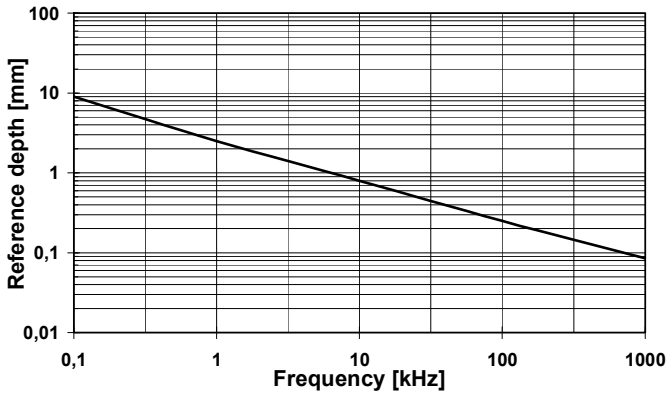


Fig. 6. Reference depth for energy absorption as function of current frequency for aluminum (after [10]).

It may be concluded that if reference depth is for example less than 0,5 mm, heating of aluminum requires a frequency higher than 10 kHz.
A more delicate problem occurs in the case of thin-walled tubes, when reference depth should be smaller than the wall thickness. The influence of frequency on the energy provided by magnetic fields to a tube with thin wall is illustrated in figure 7.

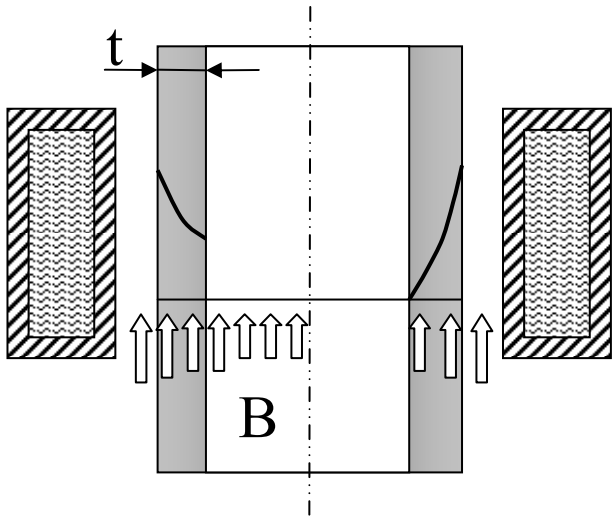


Fig. 7. Influence of frequency on energy transfer to a metallic tube [10].

Left side represents the case when the frequency is lower. Some of the field lines of induction *B* penetrate the interior of the tube, having a wall thickness *t*. The lines which are on the interior of metallic tube cannot

induce any currents and their energy is lost inside the tube. The efficiency of power transmission is low.
On the right side of figure 7 the frequency is higher and the reference depth is smaller, corresponding with the wall thickness *t* of the tube. All the induction lines B are confined inside the metallic wall and produce heating. Therefore the power transmission is very efficient.
The power P effectively absorbed by a metallic workpiece can be calculated by the following relation:

$$P = K\frac{\rho}{\delta}AH^2 \qquad (2)$$

Where *K* is the power transmission factor dependent on part geometry, materials properties and frequency, δ and ρ represent respectively the reference depth and the electrical resistivity, *A* is the workpiece surface exposed to magnetic field and *H* is the intensity of magnetic field on the workpiece surface.
In the case of tubes the factor *K* has a well-pronounced maximum value, especially when the walls are thin in comparison with tube diameter (small *t/d* ratio), as seen in figure 8, where power transfer factor is represented as a function of t/δ ratio, between wall thickness and reference depth.
Therefore in the case of thin-walled tubes a very important concern is to select field frequencies providing *K* values close to maximum, i.e. optimum electric dimensions.

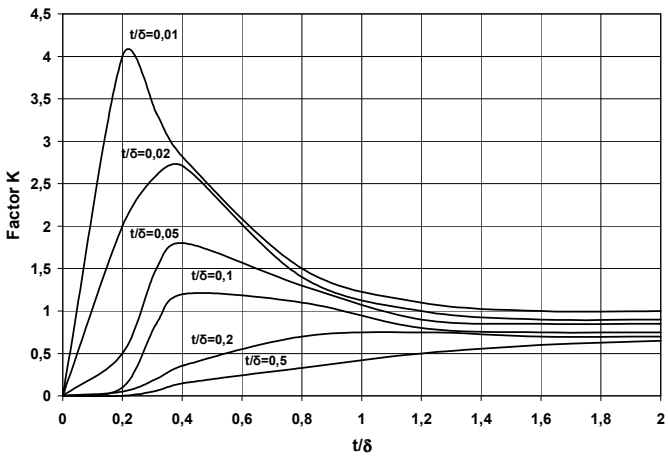


Fig 8. Power transfer factor for tubes [10].

Electrical dimensions of a tube may be described by a product between t/δ and d/δ, where *d* represents outer diameter of tube. Maximum of the brazing coil efficiency corresponds to td/δ^2=3,5 [10].
It results that for a diameter of 10 mm and wall thickness of 1,5 millimeters an optimum transfer of heating power should be achieved for the reference depth of approximately 0,5 mm:

$$\delta = \sqrt{\frac{3{,}5}{t \cdot d}} = \sqrt{\frac{3{,}5}{1{,}5 \cdot 10}} = 0{,}48 \text{ [mm]} \qquad (3)$$

For that reason, if figure 6 is considered for heating of aluminum, the optimum frequency for brazing heating should be between 10 and 100 kHz.

4.3 Equipment and tool design

Experiments have been pursued on a laboratory equipment (figure 9), which consists of a power supply, having a nominal power of 12 kW with variable frequency (1), a heating station with step-down transformer and capacitors (2) and a specially designed induction tool (3).

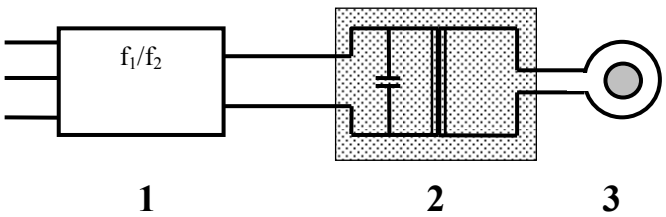


Fig. 9. Composition of brazing equipment.

The energy is provided to the brazed components, which are positioned relatively to induction tool by a special device, designed for this purpose. The experimental setup is presented in figure 10.

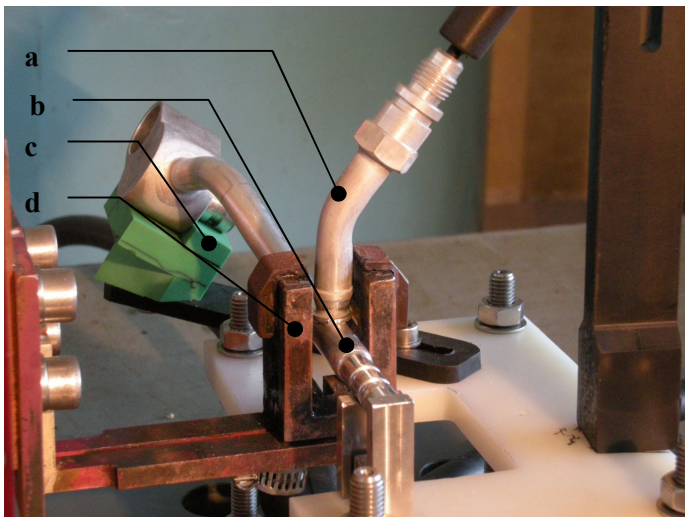


Fig. 10. Experimental setup for induction brazing: a - vertical tube; b – horizontal tube; c – positioning device; d – inductor.

Considering the extreme difficulty of a localized heating that should melt metallic filler without overheating the tubes, an inductor of original conception has been also developed (figure 11).
The inductor consists of two connection plates (1) supporting an induction coil (2). The coil has a special configuration, divided in 2 active loops (3) and (4), located on lateral sides of joining components. This allows a perfectly symmetrical heating of the joint.
The loops form a serial circuit, and are therefore passed through by the same high-frequency current. Portions of the coil that are not used for active heating are positioned close together, forming zones where currents have opposite directions, and magnetic fields compensate each other.
The shape of the coil allows formation of an area of optimal heating, which could be moved vertically on the joint to focus the energy in the desired area.

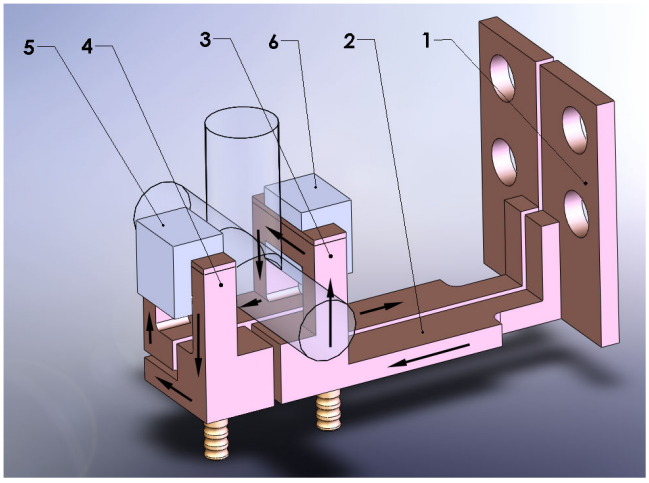


Fig. 10. Construction of tool for induction brazing.

Magnetic flux is concentrated on the joining area, to optimize energy transfer, by mean of two U-shape magnetic concentrators.

Table 1. Parameters of induction brazing.

Parameter	Value
Duration [s]	17
Voltage of high frequency generator [V]	305
Current of high frequency generator [A]	8
Voltage on inductor [V]	44
Induction frequency [kHz]	85
Brazing filler	AlSi12 Ø1,6 mm
Oxide removal	NOCOLOK® Flux

Large number of experiments has been performed in order to determine the optimum dimensions of devices, inductor and process parameters. The results are presented synthetically in Table 1.
A special problem that has been encountered and may be the cause for little extension of induction brazing is to determine the correct position between inductor and brazed components, to prevent overheating. Since the joint tubes could have different wall thicknesses and shapes, considering the high energetic density that could be achieved by induction, there is a need to determine an optimum relative position between inductor and tubes to accomplish a uniform heating of the joint area. The optimum vertical position between inductor and tubes has been simulated using the finite element method (figure 11), and the results have been calibrated by thermographical recordings with an infrared camera (figure 12).

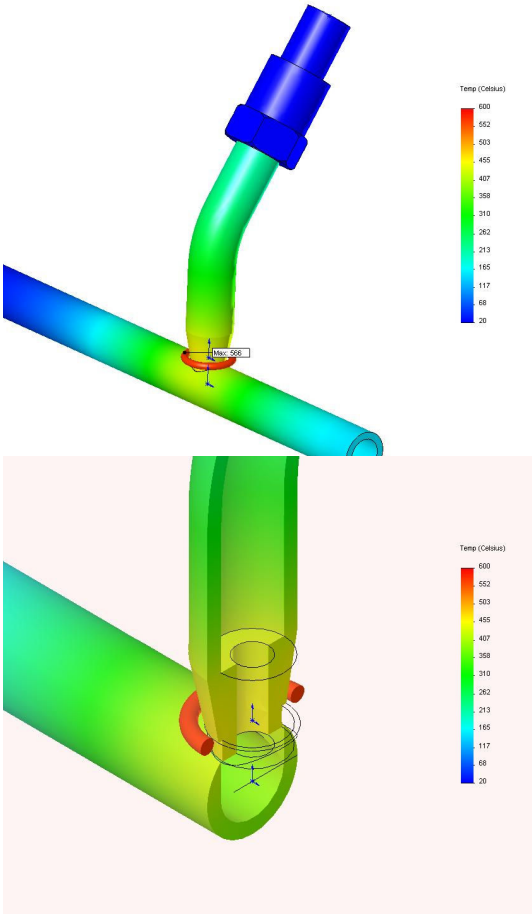


Fig. 11. Finite elements analysis of heating at 17 s

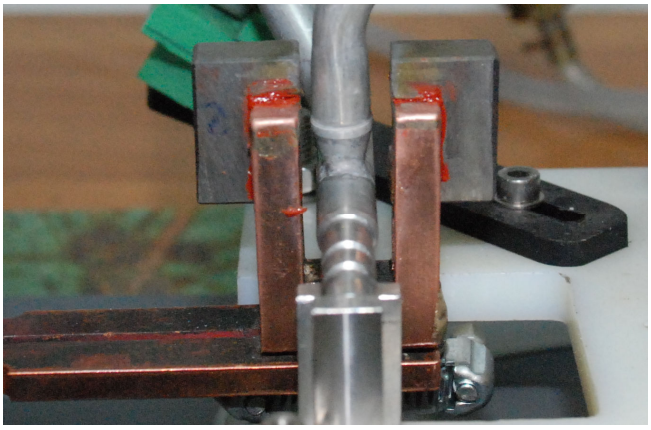
5 Analysis of inductive brazing process

It may be noticed that experiment indicates spectacular reduction of processing time to 17 seconds for inductive brazing, in comparison with 60 seconds needed for torch

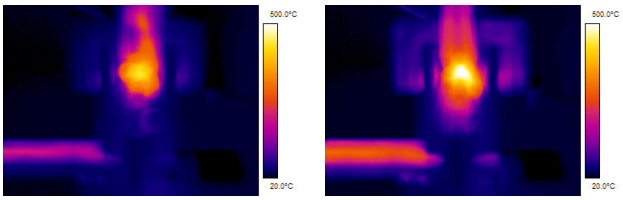
brazing. This reduction of more than 70 percent has a spectacular effect on efficiency of induction brazing.
Detailed technical and environmental analysis has been made to determine the potential benefits of extension at large-scale production of induction brazing.

5.1 Microstructure analysis

Since most of mechanical properties of brazed joints rely on appropriate material structure within the joining area, samples of both inductive and torch brazed assemblies have been evaluated using optical microscopy.

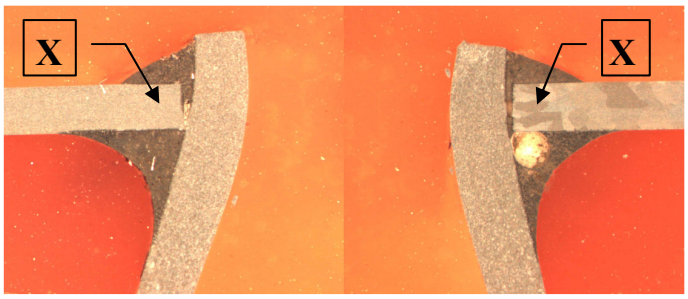


(a)



(b) (c)

Fig. 12. Thermographical analysis: (a) general view of the heated area; (b) 10 seconds; (c) 17 seconds.



(a) (b)

Fig. 13. Comparative grain size on horizontal tube: (a) inductive brazing and (b) torch brazing.

An analysis of microstructures presented in figure 13 reveals a very important advantage of induction brazing: there is usually a significant increase in the grain size of the horizontal tube, within area symbolized by "X", due to a relatively long time exposure at high temperature, during torch brazing (figure 13b), which is not present after inductive brazing (figure 13a), because overheating is less likely to occur or the exposure time is shorter.
Overheating occurs frequently during torch brazing, since localized heating is almost impossible, and explosive increase of grain size could be extended to large area of the aluminum tube, practically most of the areas under direct influence of the flame (figure 14). Although grain size increase is not directly visible, it induces extreme fragility that could produce failure in service or even on assembly line.

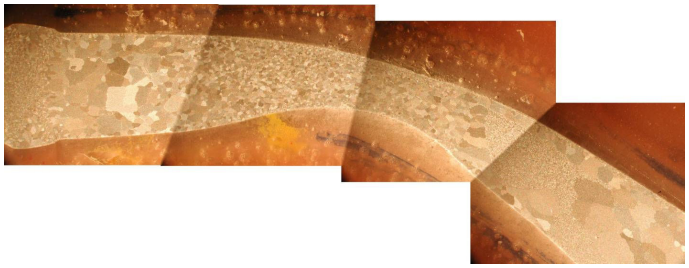
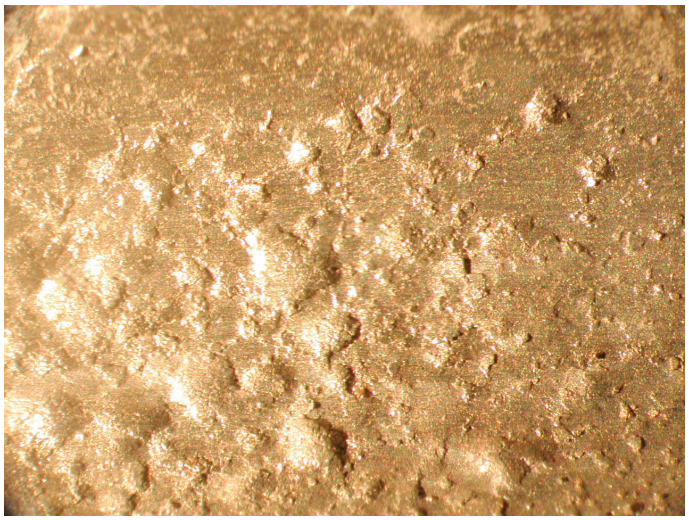
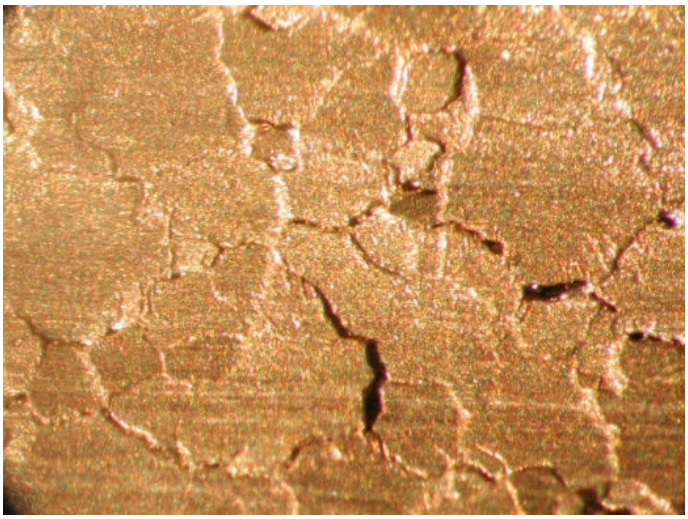


Fig.14. Grain size increase during torch heating.

This fact illustrates one of the most important advantages of inductive heating, which is the possibility to configure the thermal field in an appropriate way, to avoid overheating of base material, when the filler is melted.
The large number of scraped components at torch brazing is also caused by other damages and defects that appear frequently, and have not been reported during relatively large number of experiments of inductive brazing.

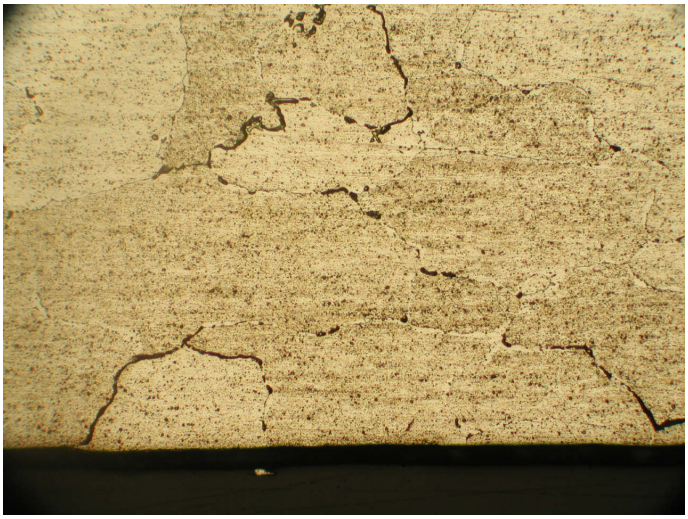


(a) Superficial bumps.

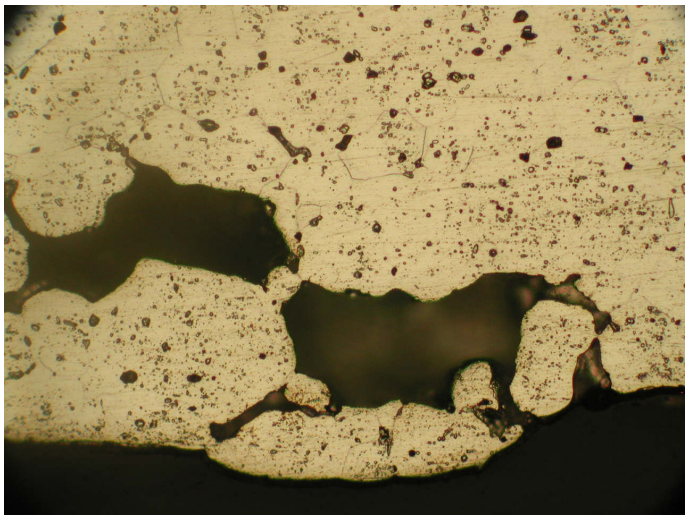


(b) Superficial cracks.
Fig. 15. Superficial defects by melting of grain limits.

For example, overheating could produce effects much more negative than grain size increase.
Since the temperature gap between total melting of brazing filler and solidus point of the tube alloy is only about 20°C, melting of grain limits of the base material is quite frequent. In this case flaws are visible macroscopically on the surface of the tube as little bumps (figure 15a) or even cracks (figure 15b).
Failure as effect of melting at grain limits could be more damaging, with the cracks propagated not only at the surface but also through the tube wall (figure 16a).
In some cases the part is losing impermeability of the wall, causing catastrophic damage in exploitation (figure 16b).



(a) Cracks penetrated inside the wall of the tube.



(b) Extended failure caused by melting of grain limits.
Figure 17. Bulk defects by melting of grain limits.

There are a large number of factors that influence heating with propane flame, and insufficient liquefaction of filler could easily take place.

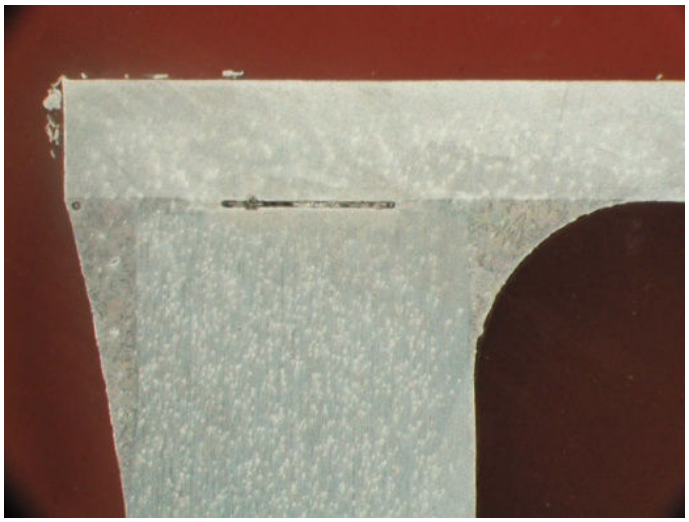


Fig. 18. Insufficient penetration of brazing filler.

If brazing filler is not hot enough and still contains solid material, infiltration is incomplete, and liquid metal does not penetrate enough between parts, producing smaller joining area and less resistant joints (figure 18).
Incomplete melting of the filler is also responsible for an exaggerated proportion of pores (figure 19), which not only reduces resistance of joint, but affects the tight sealing of the tube assembly.

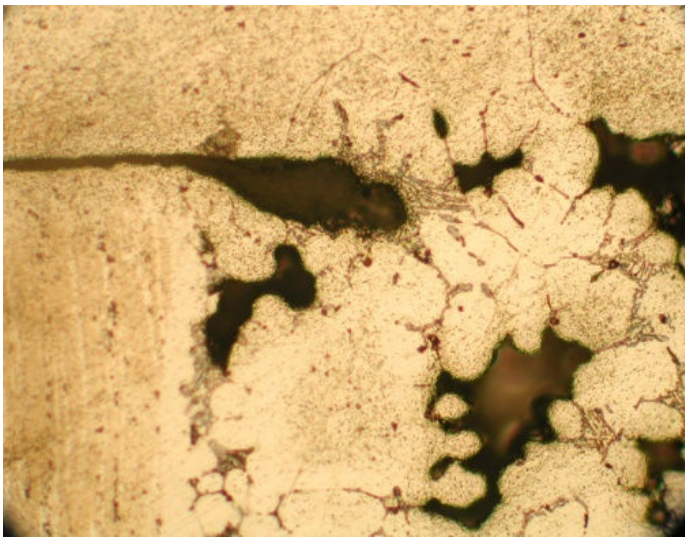
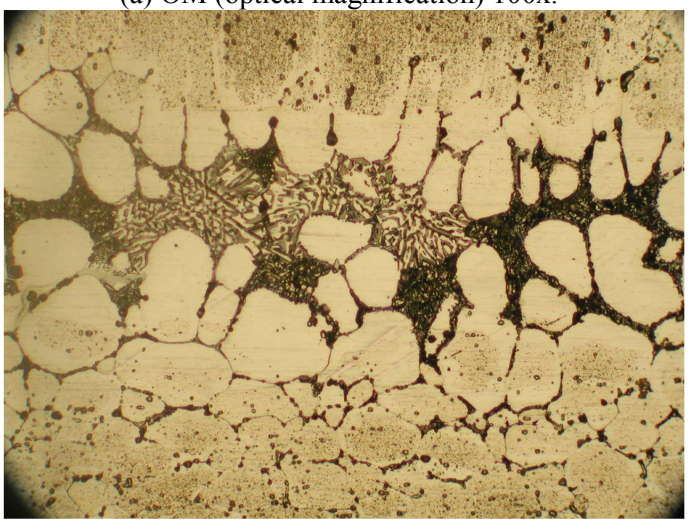


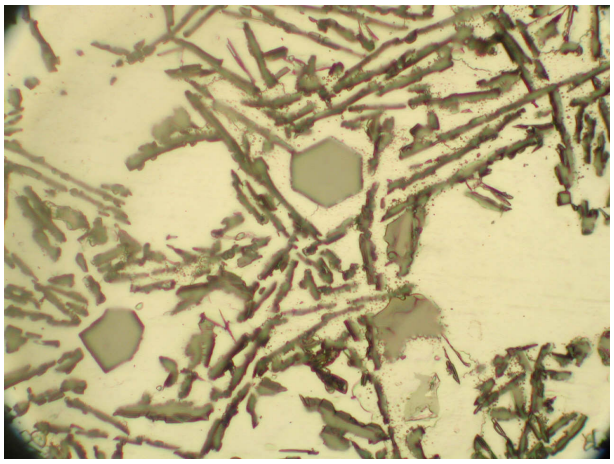
Fig. 19. Increased proportion of pores.

Torch brazing could have another shortcoming that is also related with over exposition to heat, in terms of both high temperature and longer duration, which promotes formation of diffusion phases.

(a) OM (optical magnification) 100x.



(b) OM 200x.



(c) OM 500x.

Fig. 20. Fragile eutectic produced by excessive diffusion.

The relatively high quantity of heat accumulated by metallic components also causes slower cooling rates. In this respect silicon diffusion from filler to components has been reported in several cases. As effect a rather fragile Al-Si eutectic is formed at grain limits of the tube material, reducing mechanical properties and being responsible for damage in exploitation or during general assembling (figure 20a, b and c).

5.2 Energy consumption

An important criterion to evaluate both the environmental and economic potential effect of extension of induction brazing is the energy consumption for assembling the considered aluminum component.

Industrial torch brazing is based on propane burning. The gas consumption for each brazed joint has been evaluated at 0.003568 m^3N, based on general consumption of an assembling line for the annual production. This value includes also consumptions for scraped parts, daily setup of the machine, etc.

If an average combustion value of 95800 kJ/m^3N is considered for propane, the total energy need for torch brazing of one component is about 342 kJ.

The electric power needed by the high frequency generator in experimental condition has been evaluated using the wattmeter method, and is about 65% of the nominal power, i.e. 7.8 kW. The total consumption for a cycle of 17 seconds is 136.2 kJ.

It may be concluded that extension of induction brazing would produce a considerable energy saving, of more than 60 percent, as seen in figure 21.

Considering the large scale production of this kind of components, which could reach tens of millions of units every year, the total saving of energy consumption will

arrive at very important values, so both economical and environmental benefits would be served by switching to induction heating.

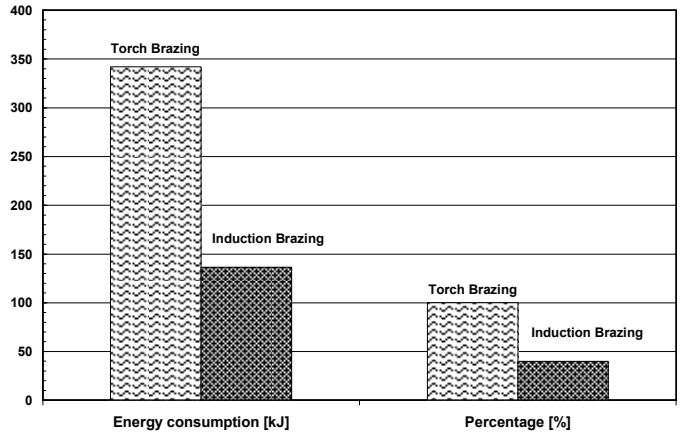


Fig. 21. Estimation of energy consumption for torch and induction brazing.

3.3 Carbon dioxide emission

It is well known that induction heating has no *direct* carbon dioxide emissions, which means that replacing torch brazing will reduce completely all carbon dioxide, which results from propane burnout.

The complete burning reaction of propane can be written:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \qquad (4)$$

The consequence of this equation is that every burned mol of propane will produce 3 mol of carbon dioxide. For this reason, torch brazing of one component will burn in air 0.003568 m^3N (3.568 liters) of propane and will produce three times more carbon dioxide, which means 0.010704 m^3N (10.704 liters).

Since one cubic meter of carbon dioxide weights 1964.28 grams, the mass of carbon dioxide produced for every component assembled by mean of torch brazing reaches approximately 21 grams.

Considering the actual extensive use of torch heating for the manufacturing industry, including brazing and welding, it may be concluded that extension of induction heating will bring important benefits for reduction of direct greenhouse gas emissions.

6 Conclusions

Experimental researches revealed that extension of induction heating for brazing has several important technical, economical and environmental advantages over the classical torch brazing, which is extensively used in assembling aluminum tubes for automotive industry:

- Direct carbon dioxide emissions produced by fossil fuel burning are totally eliminated, since heating is electric. The exclusive use of electric energy may propagate in manufacturing industry all advances achieved in energy production toward environment-friendly technologies;
- Specific energy consumptions are significantly reduced, with more than 60 %, which may also have considerable economic and environmental effects. The energy savings are produced by shorter heating times and better control of the thermal field within the joining area;
- Microscopic investigations of samples brazed by induction in experimental conditions proved that defects related with inappropriate heating are totally eliminated. Structural flaws of the base material and brazing filler, which are quite frequent in torch brazing and are mostly produced by factors related with the flame stability, are less likely to occur during inductive brazing, since all the setup parameters are electric and the process has a better stability and reproducibility.

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