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Some technological features for fabrication of accelerating structures

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Abstract: The distribution and control of temperature analyses during the brazing of lengthy accelerating structures, by induction heating usage, have been carried out. The problem of individual elements positioning, relative to each other during brazing, is solved. The results of metallographic studies for brazing zones are shown.

Keywords: Accelerator Subsystems and Technologies; Accelerator Applications

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Contents

1 Introduction

A research review in the field of advanced copper accelerating structures manufacturing has shown that their need in technology has significantly increased in recent years [1]. So far, a large amount of experimental material on the formation regularities for joints of copper accelerating structures has been accumulated [2–4]. These structures must have the following essential properties: high-precision of surface machining, high strength, ductility, vacuum hermeticity, preserving the original dimensions (the internal volume must not be changed) of products.

The development and manufacturing of an accelerating structure is a difficult technology and typically involves the following steps:

1. Uniform structures are received. Heat treatment of the blank before mechanical processing. Processing of elements to receive a low roughness of surface and accuracy on special high precision machines by high effective lubricant usage, during the machining process, as well as effective removing of chips from the machining zone. Measurement of element sizes by non-contact method.

2. Cleaning of the received elements using electro-chemical polishing, ultrasonic cleaning, rinsing and drying at not high temperatures, component preservation in vacuum conditions or in gaseous nitrogen atmosphere.

3. Setting of components, the choice of heating method, bonding of components in vacuum or controlled hydrogen and an inert atmosphere based on silver brazing method or diffusion welding.

However, in spite of the important achievements in this filed, many issues have not been studied yet, particularly the basing between separate elements of accelerating structures before joints, the scientific justification for the selection of optimal methods of heating source and characteristics of its thermal field. The problems for finding joining methods have not been solved yet: diffusion welding or vacuum brazing [2–4] and also heating load.

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During diffusion, welding the joint is formed as a result of closing up of contact surfaces at the expense of local plastic deformations at elevated temperatures. During brazing the formation of joints is realized by heating the connected materials below their melting temperature, their wetting by solder, by solder wicking into the gap and its crystallization [5]. What concerns the heating type, which is used for connecting accelerating structures, the induction heating has advantages here as compared with radiation heating.

- Heating time is shortened enough up to melted solder temperature,
- Heating takes place through the walls of protective chamber, which is made of glass, ceramics, etc., materials that absorb the electro-magnetic radiation very weakly and stay cold during equipment operation, as well as do not pollute the heated products.

The aim of this paper is to determinate the optimal parameters for the brazing technology of multiple cell copper accelerating structure using induction heating with evenly movable thermal field.

2 Calculation of thermal fields in accelerator structures

For distribution and temperature control analyses at lengthy accelerating sections' brazing (by induction heating usage), a computer modeling was carried out. The calculations were realized for a maximum quantity of structures, that can simultaneously be placed in the quartz chamber of the machine for brazing. For the initial stage the maximum heating time was taken 2700 s. As a result, the data of temperature field distribution along column height were received. The diagrams of temperature change at brazing points are presented in figure 1. The mathematical modeling allowed to divide the data into stages, depending on exposure time. In calculations, heat transfer in the column (among the cells) was carried out by thermal conductivity and radiation. The thermal conductivity correspond to contact surfaces, and the radiation for surfaces with a gap.

Heating to the final temperature (brazing temperature) was realized in differing periods of time for the first cells (1–3 joints). The bottom part of the column was in the same initial conditions — temperature of cells is 20 °C.

The data analysis shows, that for a small exposure time (100 and 200 s) the warming-up of subsequent structures on the upper structures is minor and is distributed up to 9–14 cells. By increasing the exposure time, the penetration of heat flow is increased due to heat conductivity. But there is a certain point in time at which the temperature penetration intensity along the column height is significantly reduced and practically does not change with time increase. From figure 1 it is seen, that such a moment of time is the interval within the exposure time of 900 and 1000 s. At heat exposure more than 1000 s, the column warming-up process can be regarded as static, and the same time the gradual heating of lower structures up to 60. . . 100 °C temperature is not taken into account.

One of the most important tasks of brazing process is to set the inductor movement rate through the column to receive uniform heating over the entire height. To solve this problem, we use the received data of temperature distribution along the column height.

As a defining parameter the amount of heat, which is transferred by the inductor to a specific volume of metals, is taken. For different exposure times, Q/t heat transfer velocities are received in each specific case. As well as it is necessary to add the $\Delta Q/t$ heat transferring velocity to the calculations at the expense of thermal conductivity. The principal scheme of heat transfer is shown on figure 2.

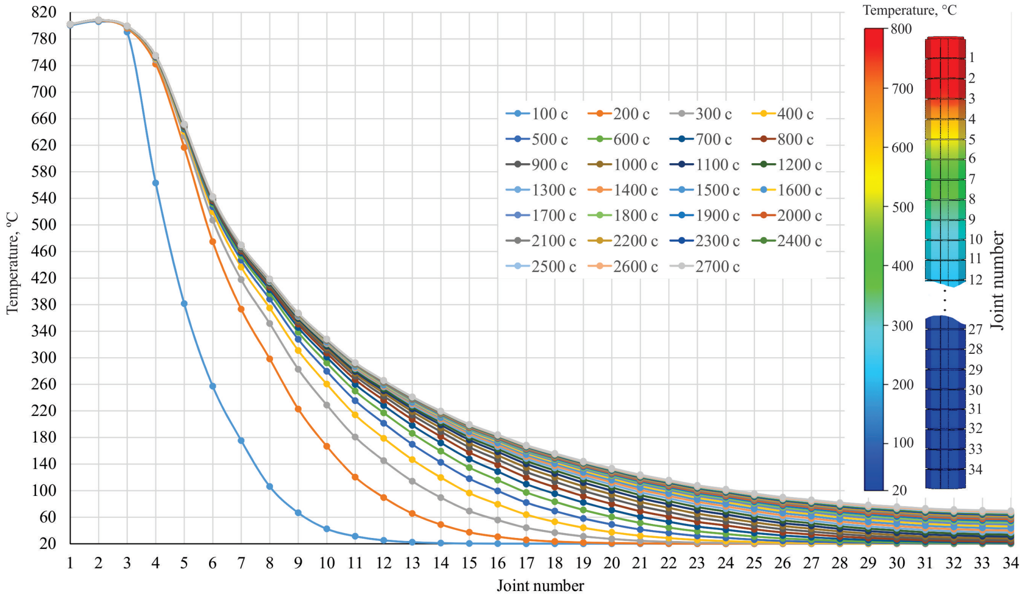

Figure 1. Temperature changes along column height.

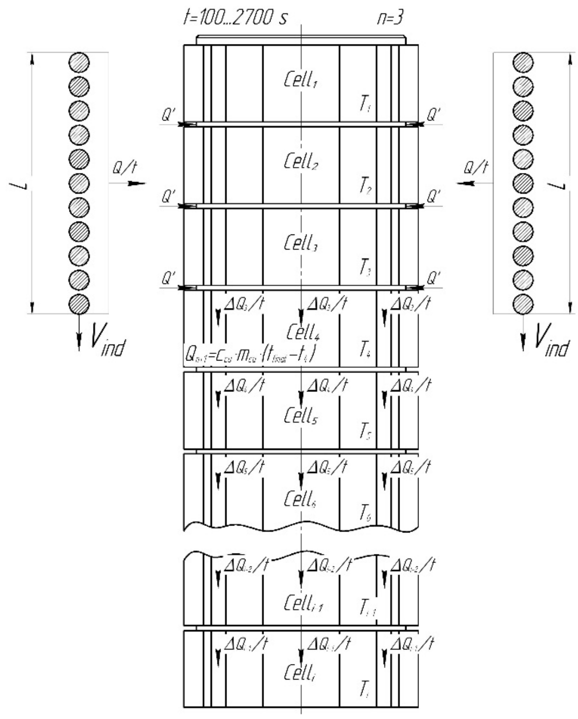

Figure 2. The principal scheme of heat transfer.

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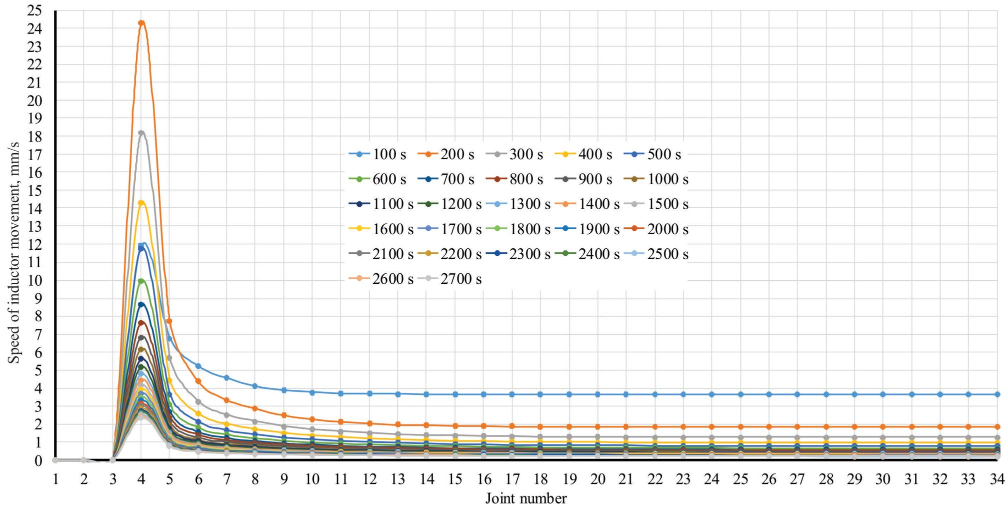

Figure 3. Changing the speed of inductor movement.

The above-mentioned factors allow to get equations for calculating the velocity of inductor movement, depending on exposure degree:

$$V_{Ind} = \frac{L}{\frac{Q'}{n \cdot c_{cu} \cdot \Delta T \cdot \frac{m_{cu}}{t}}} + \frac{Q^{\max} - Q_{n+1}}{3},$$

Where L is the inductor length, n is the quantity of simultaneously heated structures, c_{cu} is the copper heat capacity, m_{cu} = 938 grams is the weight of simultaneously heated structures, t is the exposure time, Q' is the amount of heat required to heat each subsequent cell, $Q^{\max}$ is the maximum amount of heat required to heat a cell from the minimum temperature to the one set, Q_{n+1} is the amount of heat generated from the thermal conductivity.

The results of calculations for the velocity of inductor movement are shown in figure 3.

As is seen from the figure, the velocity of inductor movement for all exposures has variable values along the column height. At the beginning of movement, the inductor speed should be high for the fast passage of sufficiently heated joints. The difference of inductor moving velocities for 100 s and 200 s heating time is a result of various amount of heat, which was transferred to the subsequent acceleration structures from the first heated ones. Thus, for 100 s the amount of heat transferred to bottom cells is lower than for 200 s. As can be seen from figure 1, by further heating time increase the amount of heat transferred to bottom cells, is also increased. For heating time 100 s and 200 s, the difference of temperature in fourth joint is 200 °C, which is affects the inductor moving velocity. Subsequently, the speed of inductor movement is decreasing and at 13–15 cells becomes constant. It should also be noted, that, considering the inductor length, the last 3 structures will simultaneously be heated and the inductor speed will be equal to 0. After reaching the desired temperature the inductive heating will be switched off. The difference in inductor moving velocities is not more than 15% as referred to the minimum.

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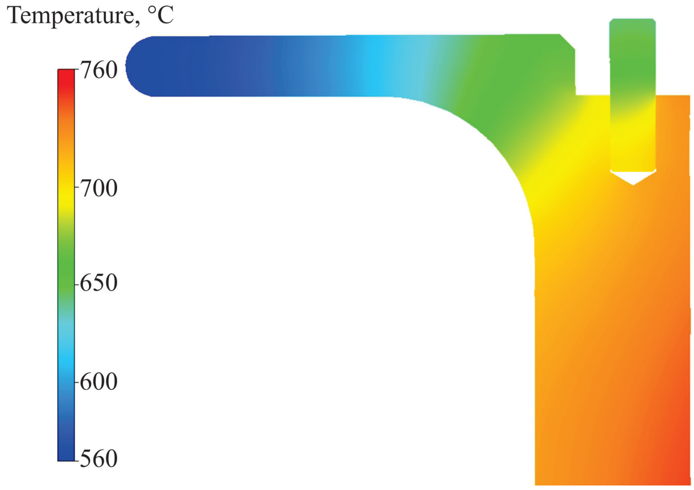

Figure 4. Temperature distribution in the cross section.

3 Positions of individual sections in accelerating structures

Different types of accelerating structures are used in acceleration technology. One of the most important parameters during assembling and brazing of accelerating structures is the positioning accuracy of elements relative to each other. At the same time, this problem can simply be solved for the case of a single concentric central hole. For the rest, an individual approach for each type is required.

For solving the problem of structures positioning, which are relative to each other during brazing, as well as to avoid their mutual movement, the usage of structural element pinning is suggested. For preventing geometry violations, it is proposed to place the pins on planes for brazing. The pins are of 304L stainless steel with a diameter of 3 mm. To position each pair of accelerating structures, 2 pins are applied. During brazing all main components are heated and change their sizes. At the expense of different thermal expansion coefficients, fields of compression stresses emerge between elements, which can cause irreversible shape distortions at sufficiently large values.

For determining stress fields, which appear at the point of pin and accelerating structure contact, a computer simulation was carried out by the method of finite elements. In view of significantly smaller sizes of the pin, as compared to the accelerating structure, the mutual influence of pins on each other can be neglected. The calculations were performed for a single pin at complete accelerating structure heating. In this case, the results obtained for a single pin, will be similar for the other two.

The metal heating uniformity depends on the overall quantity and dimensions of pins in case of pin positioning usage. In general, the influence of pins on uniform heating depends on their significant size and mass against acceleration structure. It can also be evident at accelerated heating. However, the aforementioned features are not characteristic to the reviewed conditions of brazing. Therefore, the presence of pins will not influence the uniform heating.

In figure 4 the temperature field distribution in the cross section of the accelerating structure with a pin is shown.

The analysis was performed for a definite warm-up period of the accelerating structure, which was 2700 s. Wherein, the final temperature was taken at 700 °C. This temperature was taken based

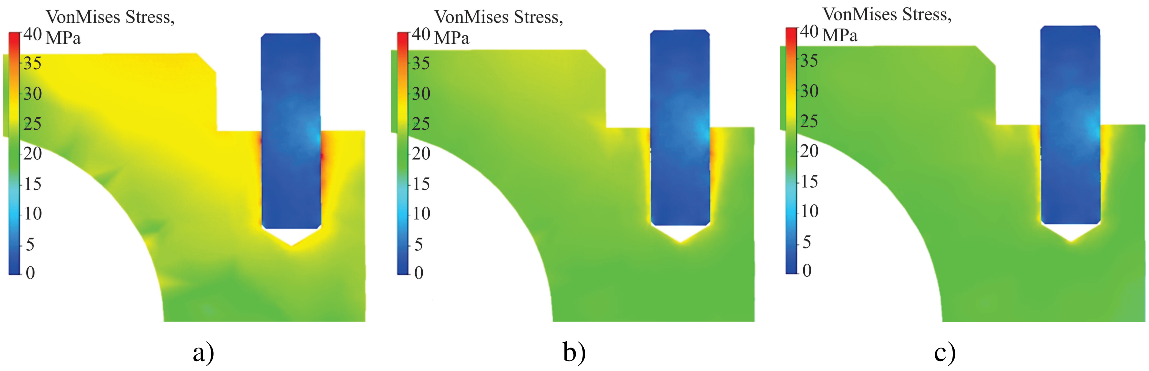

Figure 5. Stress fields on copper structure: a — 200 s heat, b — 700 s heat, c — 2700 s heat.

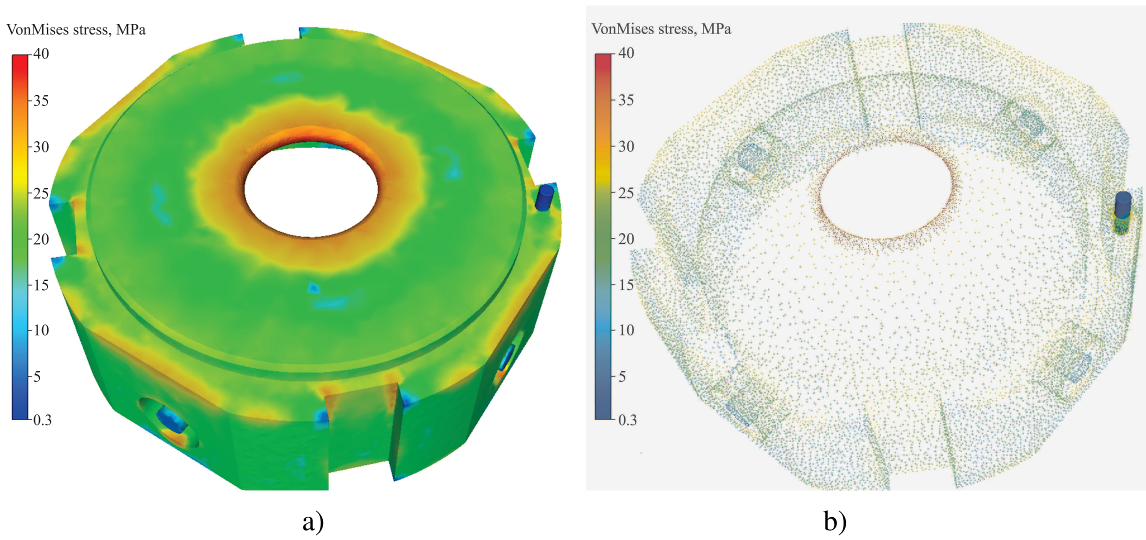

Figure 6. Stress fields on structure surface: a — on copper structure surface, b — on pin surface.

on the properties of the material being assessed (copper). At 700 °C temperature copper turns into a soft material, resulting in a reduced stress on the surface of the hole, owning to intensive recrystallization.

The stress pattern on the inner surface of copper structure in different time periods is shown in figure 5.

As can be seen from the figure, after heated for 700 s the stress pattern is only slightly changed. It is also worth mentioning that the stress localization is close to the hole and does not extend deep into the metal. The general model form, with stress results at the surface, are shown in figure 6.

In modelling the pin was taken to enters the hole with ease without a gap between surfaces. Studies on pre-stressed tension of surfaces were not carried out. The results of stress distribution on surfaces of pin holes are shown in figure 7. The changing of yield stress for copper depending on temperature is shown on figure 8.

As can be seen from the figure, the effect of pin temperature expansion starts at 30 s. The positive value of stress points to the hole expansion as a result of heating, but the subsequent stress

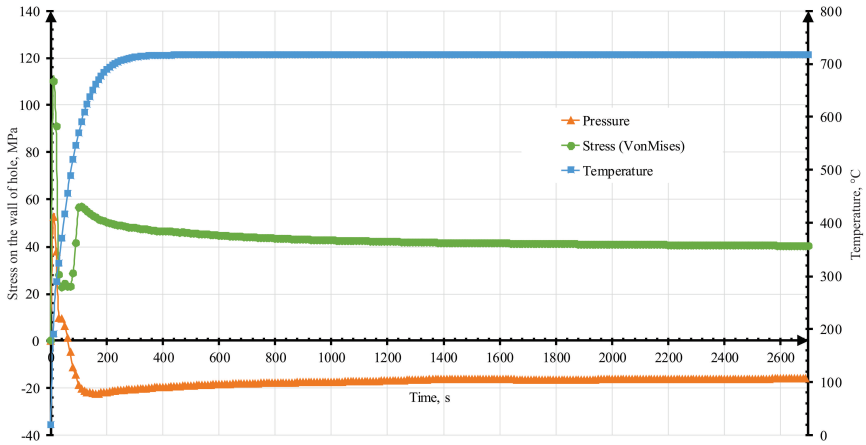

Figure 7. The diagram of temperature and pressure changes at the surface of the hole.

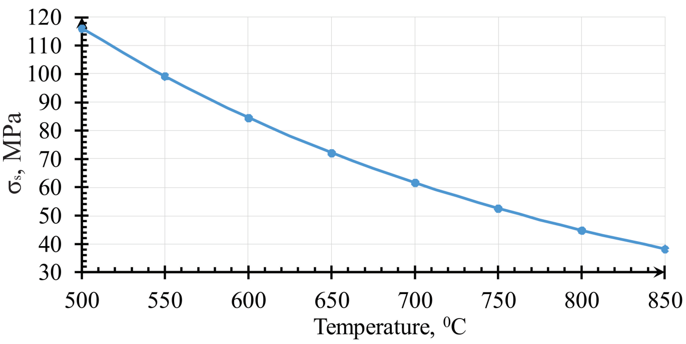

Figure 8. Yield stress for copper depending on temperature.

transition into the negative region indicates surface compressions. The surface compression starts at 60 s from the structure heat and continues till its end.

Wherein, the intensity of surface compression first increases and then decreases. In the final heating stage the stress on surface practically remains unchanged and gradually decreases. As mentioned earlier, the stress fields remain virtually unchanged. It should be noted that the results obtained can be extended by using different boundary conditions for this problem, as well as by heating speeds of structure.

4 Experimental part

For brazing with solder Ag72Cu28, samples of M1 copper with 25 mm diameter were made.

The research was conducted in two variants:

- A foil of 50μm was set between the surfaces,

- In the corners of brazed copper elements a groove and a gap for solder flow were made.

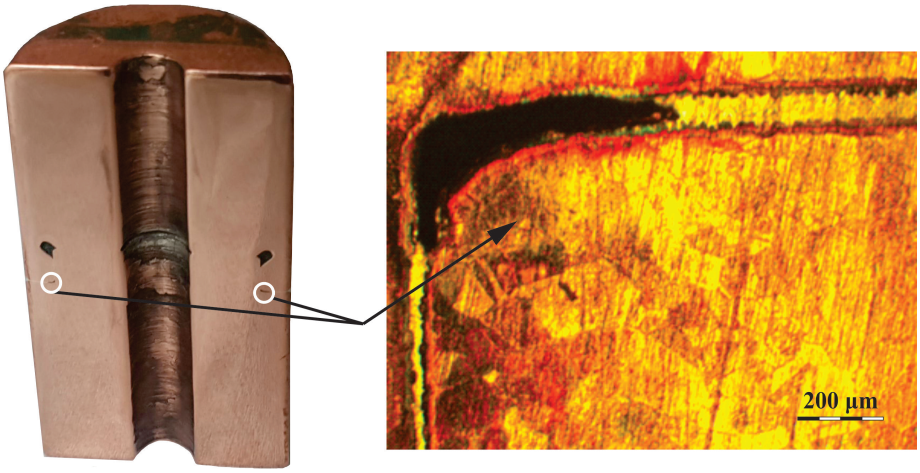

Figure 9. Microstructure of brazed copper cells (x50).

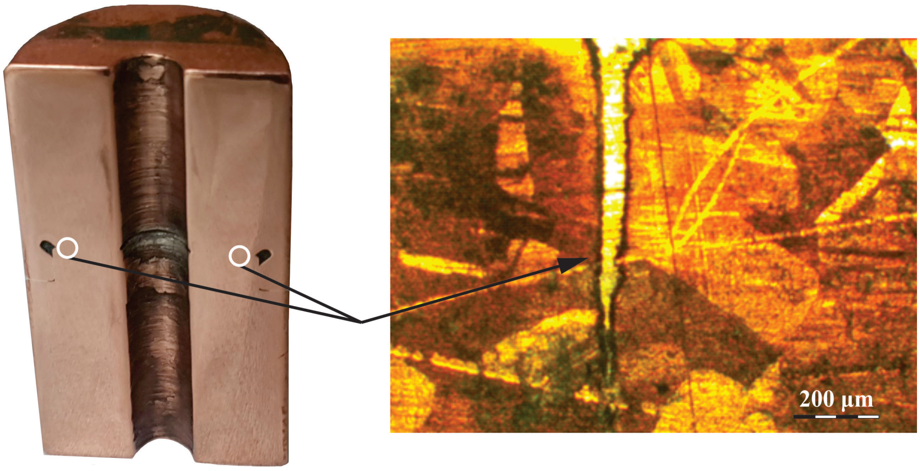

Figure 10. Microstructure of brazed copper cells (x50).

In the first variant, the silver foil usage was necessary, to apply a little pressure for plastic deformation localization; in that case the excessive solder goes into the working volume of the components, that is undesirable.

In the second variant, the more the tilt angle is, the more the void around the groove is (figure 9). The investigations have shown that in our case the optimal gap for solder flowing is 0.07 mm (figure 10).

The brazing of items and the location of grooves for soldering were developed according to the principle of groove fabrication for the inner solder, where the embedded solder rapidly flows into the tapering gap [6], since the filling pressure increases at a reduced gap width, the items are collected with a specific gap, which tapers in the direction of solder flow.

In figure 11 the manufactured joint of copper cups is presented, which is conditionally divided into two parts: the first part serves as a barrier for the liquid solder to flow into the working area of the accelerating structure and the second one ensures silver soldering without copper component deformation, since there is no external pressure.

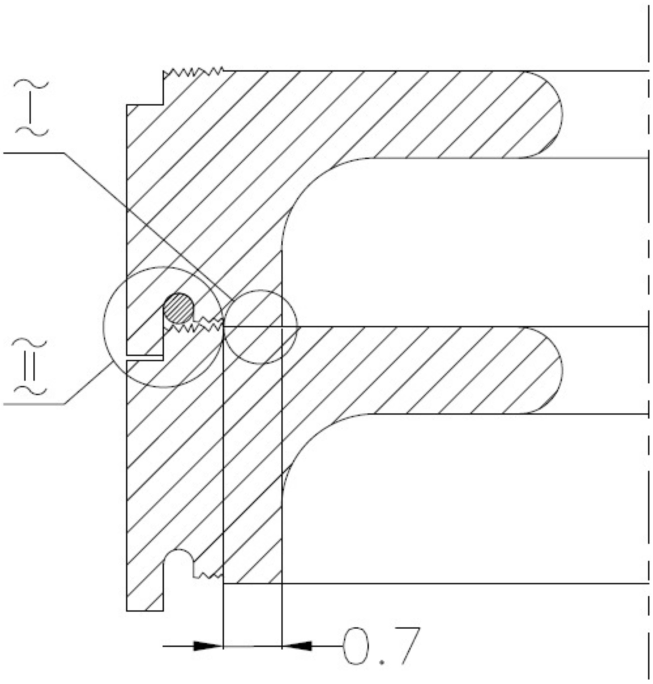

Figure 11. The joint of brazed copper cups.

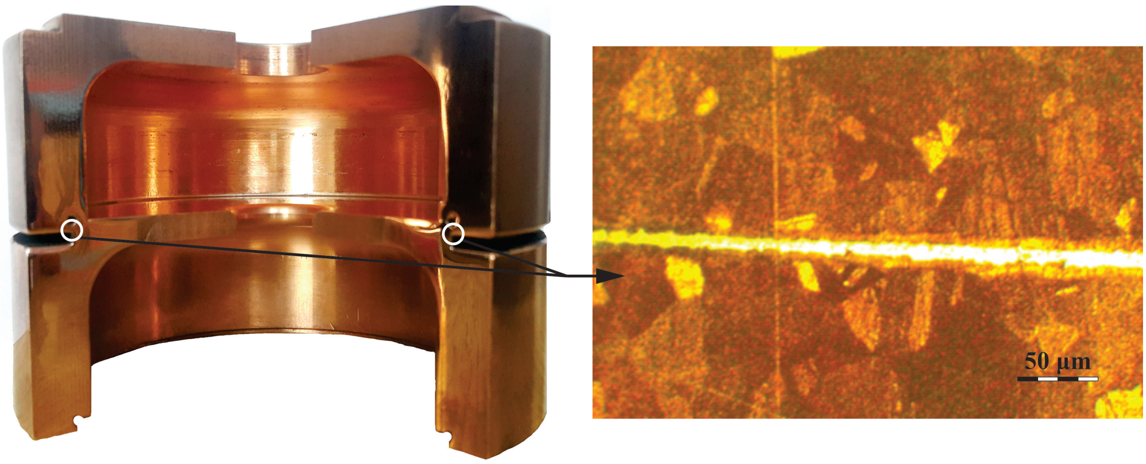

Figure 12. Metallographic structures for the brazing zone of copper cells.

In the process of accelerating structure brazing the preliminary compression of elements for obtaining quality products plays a decisive role. The load value determines a complete closure of lock 1, which prevents the solder from getting into the inner space of the accelerating structure. The force choice for compression is an actual issue in accelerating structure obtainment questions.

The brazing of copper accelerating sections was realized in P= 1.73 $*10^{-9}$MPa vacuum, with silver solder (72% Ag + 28% Cu), under 0.45kg/mm2 compression pressure along the whole area of brazing cells to ensure the necessary contact, and the brazed accelerating structures change their original size for almost 16 μm. Figure 12 shows the metallographic structure for the joint zone in

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Figure 13. Microstructure of copper joints (x200).

region 1, the total closure of the lock and the stopping point of the melted solder are seen (figure 12). It is necessary to mention that at compression pressure increase till silver solder (72% Ag + 28% Cu) melting, a diffusion welding occurs at sector 1 (figure 13).

It is seen from the figure that the section border is preserved and a general formation of grains is observed.

In figure 14 an installation for soldering the accelerating structure, 1.2 m in length, is presented [7]. The developed machine allows to ensure optimum brazing regimes at the junction of every two cells along the entire length of the accelerating structure. The pressure constancy is provided by the pneumatic cylinder control system, which decreases the load as the heater moves from top to bottom; the permanent time constancy of brazing process and heating temperature is provided by inductor thermal field movement according to the thermal conductivity of copper.

In figure 15 the electro-dynamic measurements of brazed copper accelerating structures are presented.

It should be noted that the already conducted researches in work [3], for a similar machine, had some shortcomings, which are as follows; the electromagnetic field of the inductor distorts the parameters from the potentiometer and accordingly the parameters of the electromagnet are changed.

The electro-dynamical measurements have shown that after brazing the electro-dynamical parameters of the accelerating section have become more close to the calculated parameters.

The measurements have been carried out according to the principle of S11 reflection coefficient by ZVB14 R&S vector-network analyzer. The results of accelerating structure measuring revealed that the difference between the calculated and experimentally obtained frequency is 70 MHz at the resonance frequency 3GHz, representing 2.3%.

A greater approximation to the calculated parameters of electro-dynamic measurements is achieved by tuning.

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Figure 14. Installation for vacuum soldering of accelerating copper structures (1. Accelerating structure, 2. Quartz chamber, 3. Inductor, 4. Directive, 5. Fore vacuum pump, 6. Turbomolecular pump, 7. Vacuum gauge controller, 8. Vacuum gauge, 9. Turbomolecular pump controller, 10. Redactor for inductor displacement, 11. Dynamometer, 12. pneumatic cylinder).

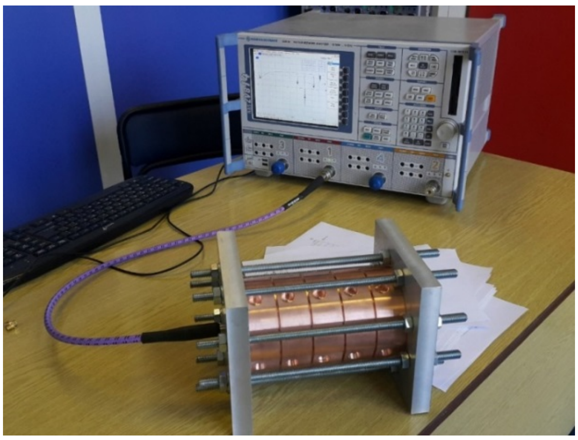

Figure 15. Electro-dynamical measurements of accelerating structures after brazing.

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5 Conclusion

1. A new approach for connecting accelerating structures has been developed, the principle of which is to heat and move the thermal field according to the thermal conductivity of copper.

2. By calculation and experimental methods, the thermal stress has been determined at fixing the two copper cells by the third element (pin) with different close coefficients of thermal expansion.

3. For ensuring a quality connection, the accelerating structures in joints of each element are conditionally divided into two parts: the first part serves as a barrier for the liquid solder to flow into the working area of the accelerating structure and the second one ensures silver soldering without copper component deformation, since there is no external pressure.

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