Influence of the relative position of base materials in microwave bonding reactor on quality of process

R.C. Marin[1,2], **M. Ciornei**[1,3], **I.D. Savu**[1], **S.V. Savu**[1]

[1]Universitatea din Craiova, [2]SC BORDNETZE SRL, PhD. Student Universitatea din Craiova,
[3]Inspectoratul Teritorial de Muncă Mehedinți, PhD. Student Universitatea din Craiova

E-mail: danut.savu@ymail.com, sorin.savu@yahoo.com, roby_roby126@yahoo.com, mirelaciornei@gmail.com

Keywords

Microwave bonding, ceramic materials, nanostructured sensor

1. Introduction

Diffusion bonding or diffusion welding is a solid-state welding technique used in metalworking, capable of joining similar and dissimilar metals. It operates on the principle of solid-state diffusion, wherein the atoms of two solid, metallic surfaces intersperse themselves over time. Elevated temperature and pressure causes accelerated creep in the materials [8].

Grain boundaries and raw material migrate and gaps between the two surfaces are reduced to isolated pores. Material begins to diffuse across the boundary of the abutting surfaces, blending this material boundary and creating a bond [9].

In microwave heating, a polar molecule is subject to electromagnetic radiation at a frequency that is in the microwave range. The materials' exposure to microwave energy causes rotation in the polar molecule, which results in heat being generated. This phenomenon is also referred to as dielectric heating. A polar molecule is one that has an electric dipole moment, the best known being water.

Microwave bonding is a new technonolgy that can be used in joining and microjoing of materials. It is well known that not all materials can be processed in microwave due to their properties related to absorbtion and coversion of high frequency electromagnetic waves into heat. The most attractive materials for bonding in microwave field are ceramic materials. A ceramic material that exhibits dielectric heating is referred to as a *susceptor*. The ability to self-heat when exposed to microwaves is referred to as a material's ability to couple or suscept to this electromagnetic radiation. When applied to ceramic materials, microwave processing opens up opportunities to reduce costs and energy consumption while improving productivity and material properties. However, the heating process is unstable taking into account that for some values of the temperatures, the ceramic materials become more absorbant of microwaves and the temperatures increase very fast. The thermal runaway phenomenon leads to cracks both in base materials and joints [1, 2].

In general, the temperature required to obtain sufficient joint strength is typically within the range 0.5 - 0.8 of the absolute melting point of the base material. For metal-ceramic joints, bonding temperatures up to 90 % of the metal melting point have been reported [3]. Achieving high integrity joints between ceramics and metals, however, is a challenge. The properties of ceramics that make them attractive may pose major handicaps for joint fabrication. Due to the chemical inertness of ceramics, conventional joining methods for metals cannot be used. To obtain adequate bond quality, high temperature and pressure are often required [4, 6] and bonding media with reactive elements have been used [5].

2. Design the microwave-bonding chamber

For the application of microwave bonding of ceramic materials, a reaction chamber have been designed taking into consideration the following elements:

The samples must be monitorized in terms of temperature using infrared pyrometer [7]

The samples must be monitorized in terms of video surveillance in order to control the cracking process due to potential microwave plasma discharge

The samples must be positioned inside the bonding chamber taking into account the exposure to the microwave beam; obviously for better control of the bonding process the samples can be moved upward or downward in order to obtain total exposure without microwave peaks.

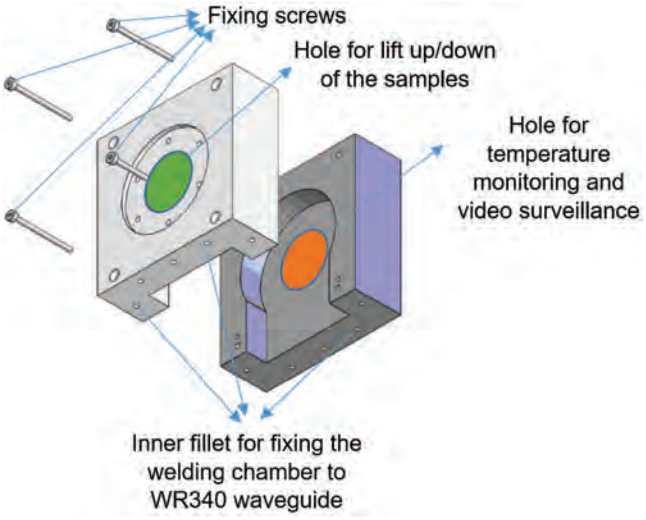

Figure 1. Bonding chamber.

The bonding chamber have been executed from duralumin being composed from two parts due to the specific fixing mode to WR340 waveguide. Also, by designing the bonding chamber in two separate parts, allows easy access to the materials which will be welded. There are two access holes in the upper and lower parts for lifting system and temperature and video surveillance access point.

3. Designing the lifting system and position sensor

The lifting system allow the welder to move upward or downward the base materials inside the bonding chamber. In addition, a proximity sensor will monitor the relative position of the samples. The operation of the system designed according to the solution presented in the previous figure involves the following: the role of the proximity sensor is to detect and monitor the vertical distance of the sample in the bonding chamber.

Knowing that in the microwave process, the maximum heating takes place at the point of maximum amplitude of the high frequency electric field intensity, but also the fact that at this point the influence of the electric field is a point (the amplitude peak corresponds to its maximum).

Therefore it is proposed, that the materials subjected to the joint, to be positioned in the middle zone of the positive alternation of the oscillating electromagnetic field. The figure below presents the sketch of lifting system.

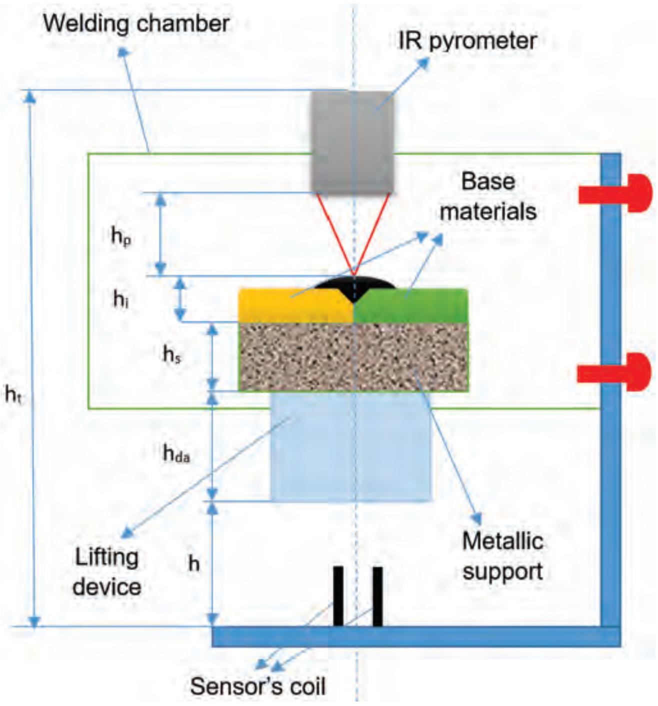

Figure 2. Lifting system with proximity sensor.

Determining the optimal height involves calculating the following parameter:

$$h = h_t - (h_p + h_i + h_s + h_{da}) \quad (1)$$

where:

- h - the optimal height adjusted and detected by the proximity sensor,
- h_t - the total height of the device,
- h_p - height given by the focal length of the pyrometer, parameter that depends on each pyrometer separately,
- h_i - total joint height (base material + weld),
- h_s - the height of the ceramic support,
- h_{da} - the height of the threaded feed system.

The parameter related to focal length of the infrared pyrometer is very important for the monitoring of the process. The lifting system can be applied to all types of pyrometers if the non-contact temperature sensors have and adjustable and independent fixing system. Having each of these factors, it can be determined and set a prescribed value in the proximity sensor so that the condition of positioning the samples to be joined in the middle of the positive alternation of the high frequency electromagnetic wave can be observed in any situation.

The verification of the notification system for different values of the height of the samples to be joined in the microwave bonding chamber is performed by implementing equation 1 in a spreadsheet for which the sensor characteristic will be raised. A figure of lifting system is presented below.

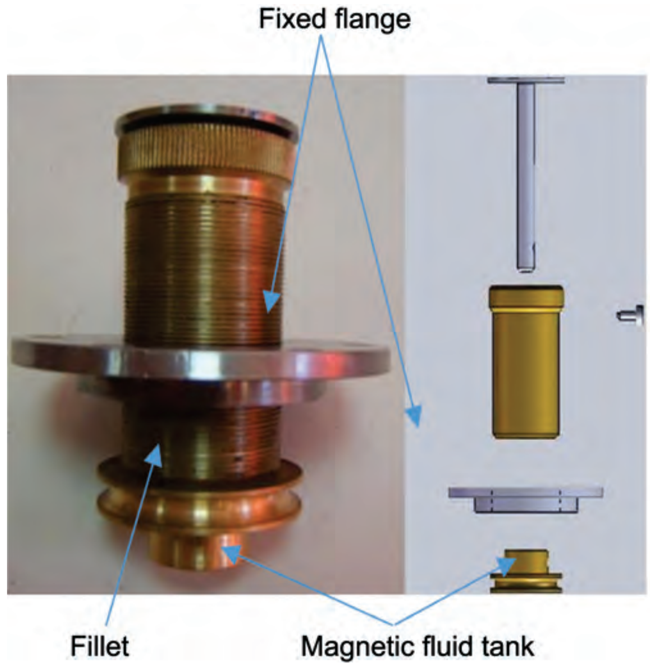

Figure 3. Detail of lifting system used in experiments.

The verification of the sensor is performed by changing the thickness of the materials subjected to the joint which can be equivalent to changing the position on their height under conditions of a fixed thickness.

Table 1. Limits of the lifting system.

h [mm]	h_t [mm]	h_p [mm]	h_i [mm]	h_s [mm]	h_{da} [mm]
1	63	30	2	10	20
2	63.1	30	2.1	10	20
3	63.2	30	2.2	10	20
4	63.3	30	2.3	10	20
5	63.4	30	2.4	10	20
6	63.5	30	2.5	10	20
7	63.6	30	2.6	10	20
8	63.7	30	2.7	10	20
9	63.8	30	2.8	10	20
10	63.9	30	2.9	10	20
11	64	30	3	10	20
12	64.1	30	3.1	10	20

The proximity sensor have been designed on basis of sensing properties of magnetic nanofluids introduced in the empty core of a coil. The sensor measure the distance between bottom of bonding chamber corresponding to the peak of microwaves and the location of base materials.

The magnetic fluid is fully introduced inside the coils when the lifting system is set to point zero representing h = 20 mm of the magnetic fluid column. In this case the magnetic inductance of the coils is maximum reaching about L = 107.87 µH.

From microwave point of view, this point corresponds to the peak of microwave power injected between ceramic base materials.

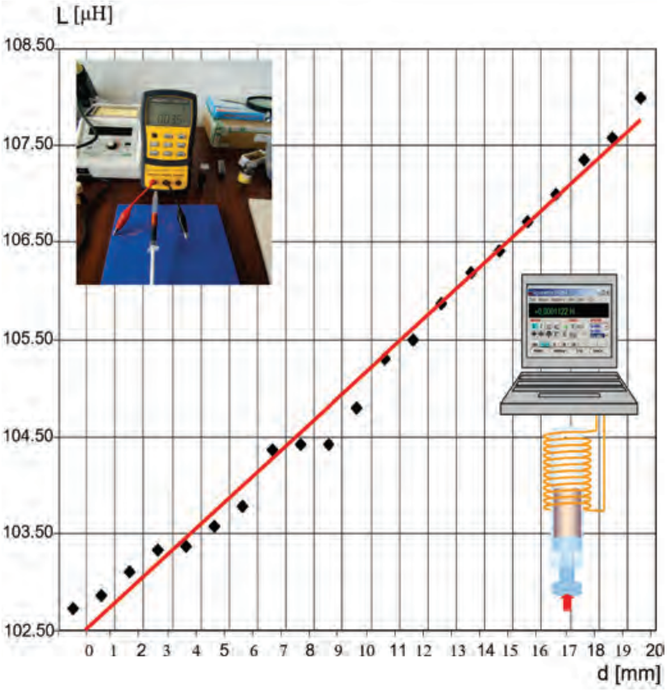

Figure 4. Preliminary test in sensing application.

The mathematical model of magnetic inductance variation is represented by the following linear equation:

$$L = 0.2682 \cdot d + 102.13 \qquad (2)$$

The principle of the sensor and preliminary measurements related to sensing are presented in figure above.

4. Experimental program

The experimental program consist of in injecting microwave power using a microwave generator with adjustable input power from 600 W to 6000 W, the heating process being controlled by a matching load impedance auto tuner. To obtain the maximum absorbed power and minimum reflected power it is necessary to match the impedance of the load to the impedance of the transmission line. In this case the load impedance has no reactive part which can pull the generator frequency, and the SWR on the line is close to the unity, so the line connecting the generator to the load is non resonant. Stubs are used for producing a pure reactance at the attachment point, reactance that varies with their length. For matching any impedance load to the impedance of the transmission line 3 stubs, that have fixed positions on the transmission line, can be used. The microwave system used in experimental application is presented in next figure.

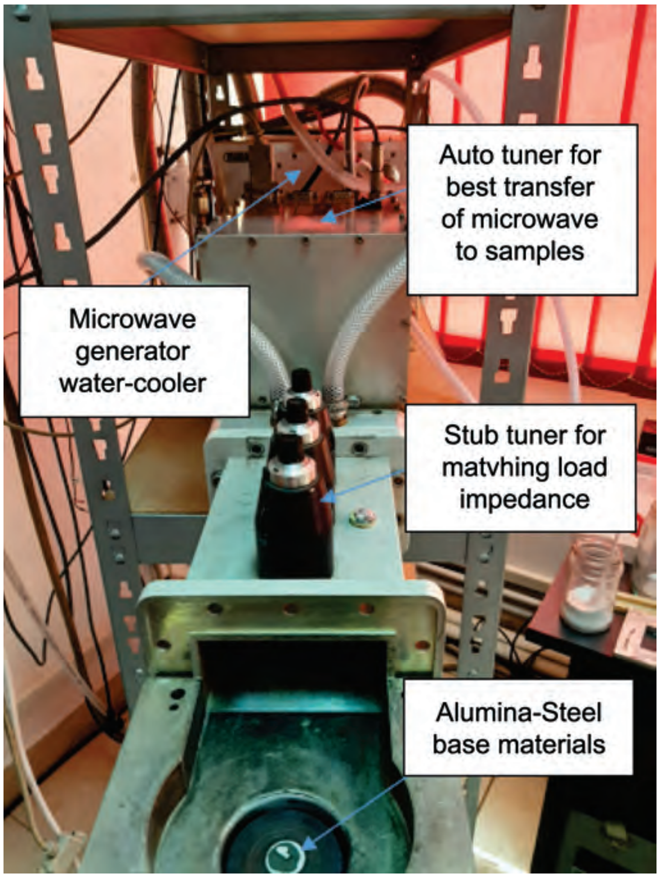

Figure 5. Microwave system for bonding ceramic-steel base materials.

The proposed parameters for bonding of base materials in microwave field are presented in table below.

Table 2. Microwave bonding parameters.

Parameter	Values
Position of the samples in the bonding chamber [mm]	0
	5
	10
Microwave power injected into base materials [W]	600
	1000
	2000

The process has begun with a low microwave power injection (P_{MW} = 600 W) with the samples positioned on the bottom of the bonding chamber. After 10 seconds the base materials started to convert the microwaves into heat. However, the bonding process was not fast and the second step was to increase the level of power to 1000 W and then to 2000 W. In both cases, the thermal runaway phenomenon occurs as and the process was unstable. Moreover, the process have been stopped at 866°C because the high electrical polarization combined with high temperatures led to arc discharge between steel and micrometric screws of the manual stub-tuners. The arc established between samples and stubs was very unstable and therefore the reflection coefficient was almost 100 %. The process has been automatically stopped by the microwave power source protection because the extension of the arc discharge could have destroyed the magnetron antenna in the microwave generator.

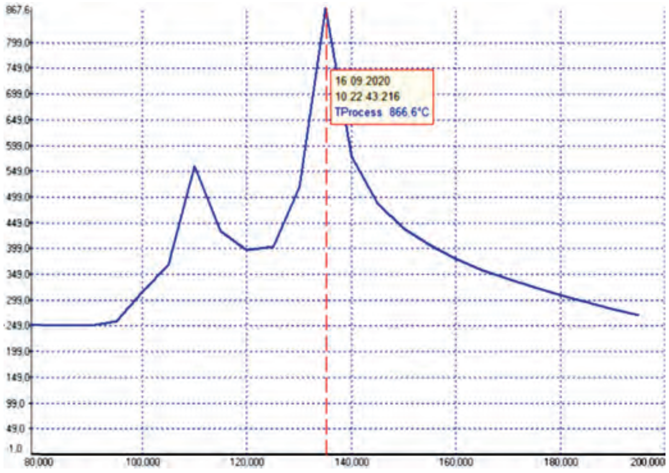

Figure 6. Thermal runaway phenomenon occured at medium and high level of microwave power.

The timeline of temperature is very short, the first peak occurring after less than 2 minutes when the temperature reaches 550°C.

One of the characteristics of thermal runaway phenomenon is related to increasing of the temperature as function of increasing the conversion rate of the microwaves into the heat. These characteristics are unique for each material, but the latest researches reported for ceramics an interval between 450°C and 800°C.

Figure 7. Thermal runaway phenomenon followed by microwave plasma.

The second peak of temperature occurs after a natural cooling in a short period, when the temperature decreases to 399°C and the process becomes stable. The second peak is more violent in temperature, which reaches a gradient of 460°C/second. The temperature increases to 867°C and even more higher if the thermal protection is cancelled. The figure above present a snapshot obtained during thermal runaway phenomenon.

All the tests performed for microwave power at 1000 W and 2000 W have led to thermal runaway phenomenon in case of samples placed on bottom of the heating chamber. Therefore, using the lift system, the samples were up to 5 mm and the process was restarted. For this place in all three bonding tests, the heating was stable and the ceramic base materials were bonded on steel support. The results of heating process are presented in the table below.

Table 3. Bonding temperatures in microwave field.

t [s]	$T_{P = 600\ W}$ [^{0}C]	$T_{P = 1000\ W}$ [^{0}C]	$T_{P = 2000\ W}$ [^{0}C]
0	0	0	0
10	187	211	334
20	221	245	389
30	270	346	467
40	312	414	555
50	425	567	686
60	602	654	786
70	657	721	899
80	699	804	945
90	743	867	1011
100	788	912	1089
110	812	966	1222
120	875	989	1267

The graph representation of the temperature evolution during bonding process is presented below. The graph that even the injected power is high, the temperature increases after a similar mathematical model. That is explained by the fact that the number and speed of polar particles inside the base materials are limited and the temperature will increase but the thermal runaway phenomenon will not occur without external influence.

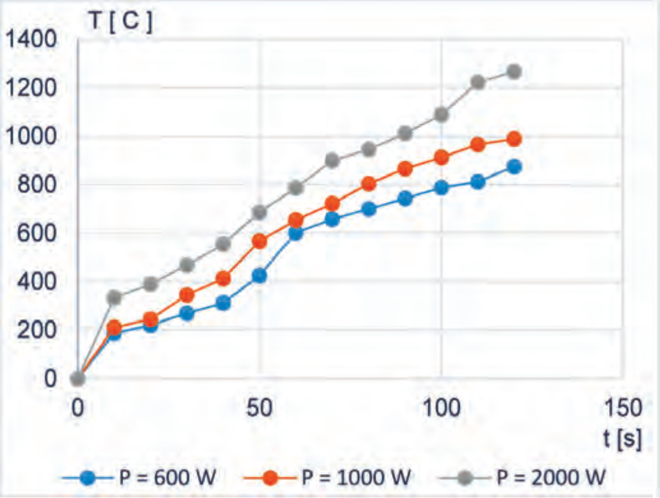

Figure 8 .Temperature evolution in base materials.

The figure below presents the alumina sample bonded on steel support. Some comments can be outlined:

- in the case of using low microwave power (P_{MW} = 600 W) the temperature has increased not so smoothly. That can be explained by the quantity of the microwaves which penetrates the ceramic materials. In this case, not all dipols have been activated form the begining. After 40 s, a first point of inflection has been established and the gradient of temperature became bigger. That can be explained by the thermal alteration of atomic structure under friction of dipoles and conversion of mechanical energy into heat.

- in the case of using medium microwave power ($P_{MW} = 1000$ W) the temperature grows steadily up to 980°C and then became stable. It means that for alumina at that temperature the microwaves even are converted into heat, the temperature rise will slow down and the heat will be propagated into ceramic material until the thermal equilibrum will be established.

In the case of using high microwave power ($P_{MW} = 2000$ W) the temperature increases faster than in the first two cases presented above. It can be mentioned that if the process will continue, the temperature will reach melting point of steels and the bonding process will be affected. However, it is important to point out that the variation of the temperature is very smoothly without sudden increases or decreases. From microwave bonding point of view this approach gives stability to the process.

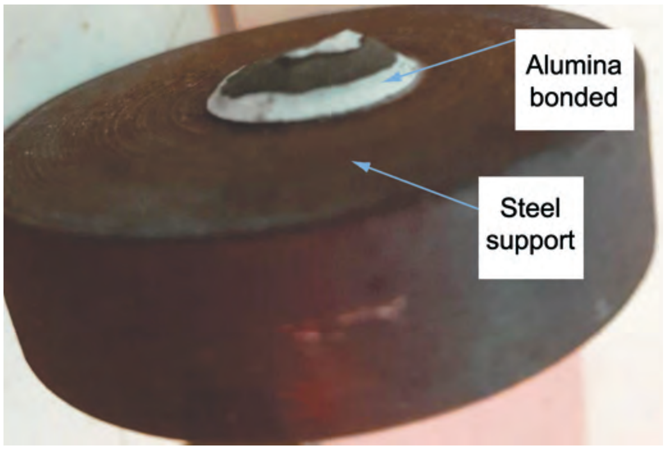

Figure 9. Alumina-steel bonded in microwave field.

Figure above presents the alumina-steel base materials bonded in microwave field. It can be observed, after a visual inspection, that the alumina sample was bonded on entire own surface. Also, it is important to mention that the bond must be tested in order to establish mechanical properties.

5. Conclusions

Bonding by diffusion of ceramic-metal base materials can be done using microwave technology. Due to alumina absorbtion properties of high frequency electromagnetic waves, the heat required by bonding process is developed very fast at the edges of both materials. The heat is transmitted through thermal conduction from ceramic materials to steel. However, the process is unstable in many cases when the thermal runaway phenomen occurs and the temperature increases very fast. The consequence of high gradient of temperature is plasma arc discharge or in some cases the base materials suffer cracks due to high polarization.

The control of microwave bonding process can be done by placing the base materials in the middle of microwave amplitude in order to avoid high frequency electromagnetic waves peaks. The peacks represent local high polarization followed by cracks in base materials. Therefore, with a lifting system monitorized by a proximity sensor, the samples can be placed in optimal position inside the heating chamber. In addition, the heating process is complete in short time if the impedance of the electric circuit is minimum. This goal can be reached in two different ways:

- Using a manual three stubs tuner where the input values must be calculated for a specific resonance (depending by each properties of the materials)
- Using a matching load impedance auto tuner which can be applied to diffferent materials without any specific setup.

The experimental research has shown that even the microwave power is increased, the thermal stability of the base materials is not changing. For different levels of microwave power (600 W, 1000 W and 2000 W), the bonding process can take place and stopped when the users consider that is necessary.

The bonding temperature of ceramic-steel base materials was decreased to 875°C that concludes that the bonding temperature of alumina-steel base materials is 62.5 % of average melting points of steels.

The bonding process of alumina-steel base materials is hard to be implemented without a matching load impedance auto tuner taking into consideration the reflection properties of metals in microwave field. For reaching bonds, in absence of matching load impedance, the process requires high level of microwave power, which can lead to unstable process.

In addition, the monitoring of temperatures developed in base material must be performed with high precautions in terms of materials emissivity. Shiny steels have lower coefficient of emissivity, but during the heating in ambient atmosphere, a thin layer of corrosion will affect the performance of infrared pyrometer. Therefore, before heating any metals is reccomended to test the metal emissivity for different temperature levels in order to be able to set correctly the non contact temperature sensor. That can be done by testing the emissivity using an additional thermal source and a thermocouple coupled with an infrared pyrometer.

References

[1]. Savu, I.D., Savu, S.V., Benga, G.C. - Thermal Runaway of the $BaCO_3 + Fe_2O_3$ Homogenous Mixture and Mechanical Alloys at the Microwave Heating, Advanced Materials Research (Volume 837), pp. 185-189, 10.4028/www.scientific.net/AMR.837.185

[2]. S.V. Savu, I. Ciupitu, N.A. Sîrbu, I.D. Savu, G.C. Benga - Microwave-resistive hybrid thermal source form soldering alloys and metal-ceramics composites, BID-ISIM, 3/2016. pp. 6-8, B+

[3]. O.M. Akselen – Diffusion bonding of ceramics, Journal of Materials Science, vol. 27, pp. 569-579, 1992

[4]. Jadoon, A.K., Employing reactive synthesis for metal to ceramic joining for high temperature applications. Journal of Materials Science, 2004. 39(2): pp. 593–604

[5]. Palit, D., Meier, A., Reaction kinetics and mechanical properties in the reactive brazing of copper to aluminum nitride, Journal of Materials Science, 2006. 41(21), pp. 7197–7209.

[6]. Zhou, Y., Microjoining and Nanojoining, CRC Press, Inc, 2008, pp.758–785.

[7]. Boţilă, L., et. al., Aplicaţii ale termografiei în infraroşu la sudarea şi examinarea nedistructivă a materialelor, Revista Sudura, An XXI, nr. 1 (2011), pp. 6-13

[8]. VanDyke, K., Streeter, G. Dreher, J., Leyrer, L. - Diffusion bonding, 2012

[9]. Kazakov, N.F. - Diffusion Bonding of Materials, Pergamon Press, 1985