CANDLE Synchrotron Research Institute

(Center for the Advancement of Natural Discoveries using Light Emission)

Vahagn Vanik Vardanyan

Vacuum Systems and Metal-Ceramic Joints in Advanced Accelerators

A Thesis

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Scientific Supervisor:

Doctor of Technical Sciences Vardan Sh. Avagyan

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Introduction

The modernity of the thesis: Particle accelerators are very important devices for fundamental and experimental research and are widely used in scientific and technological areas. They are being used in areas such as theoretical and experimental physics, chemistry, materials science, nanotechnology, biology, health care, etc. [1].

Particle accelerators are very complicated systems and they combine many spheres of science and technology: RF systems, magnetic systems, vacuum systems, thermoregulation systems, beam diagnostic technologies, etc. [2]. Only the effective combination of all the systems and subsystems gives a possibility to operate the accelerators and obtain desirable results.

There are many types of accelerators. Particle accelerators can be divided into categories based on the accelerating structures, the types of accelerated particles, beam energies, purposes (fundamental research, medical research, etc.) and other criteria [3]. Based on structure and acceleration principles the particle accelerators can be divided into linear and cyclic accelerators. The synchrotrons and colliders are cyclic accelerators. In this case, the acceleration process is performed in one cyclic beam trajectory.

There are two basic methods for acceleration of charged particles – electrostatic method based on electric fields and electromagnetic method based on radiofrequency techniques. To focus and steer the charged particles, one uses magnetic fields in accelerators [4]. Therefore, only charged particles can be accelerated in particle accelerators - electrons, protons, etc. [5].

There are many strong requirements on systems and subsystems of particle accelerators in order to achieve high accuracy of beam parameters. One of such crucial conditions for accelerators is the existence of vacuum in the beam lines. In particle accelerators a beam generation, acceleration and regulation are realized in high vacuum conditions. Vacuum gives a possibility to maintain the beam parameters during the entire acceleration processes and to increase its lifetime.

Of course, there is no such a concept as an “ideal vacuum”. Technically, everything which has a lower pressure than the atmospheric pressure of 760 mm Hg can be counted as a vacuum. In modern accelerators **Ultra High Vacuum (UHV)** is required for precise experiments. Advanced

UHV systems are required for achieving an UHV level with low enough partial pressure of residual gasses [6, 7].

It is known that different gases and gas combinations in UHV systems have different influence on the particle beam [8]. To reduce the interaction of beam with residual gases, special vacuum chambers with special pumping systems are required.

There are several physical effects taking place in the accelerators' UHV systems. For example, there are severe effects from the charged beam, severe electromagnetic irradiation, various thermal and mechanical effects and so on. The detailed properties of these effects can be different for different types of vacuum systems.

One of the important effects is the production of various gases in the vacuum chamber (known widely as outgassing). Depending on the vacuum chamber, types of the used materials and the conditions of operation, the outgassing rates can vary from high to low values. The rate of gas production in the vacuum chamber must be as low as possible during the machine's operation [9, 10]. For decreasing the rates of gas production in the vacuum chambers a special design of the vacuum-related systems (including the pumping systems, special magnets, undulators, BPM, experimental stations, etc.) is necessary [11]. The latter includes the thermo-mechanical design, the fabrication technologies, several thermal and chemical cleaning procedures. For an effective and reliable vacuum chamber, all the parameters of the beam, all the possible external influences in the vacuum chamber should be taken into account. Also, a special design of vacuum pumps aimed for special applications in the vacuum pumping systems is required [12]. In order to obtain precise beam parameters, one needs to achieve a very high vacuum level, low residual gas level and also one needs to decrease the beam-gas interactions. Dust contamination is another factor to be carefully taken into account in the UHV systems [13, 14].

It is an important requirement to decrease or avoid several other influences on the beam. For example, undesirable magnetic fields must be avoided. The materials used for UHV systems of accelerators in many cases must be non-magnetic materials.

The requirements of vacuum level depend on experimental specifications of particle accelerators, especially on the level of beam accuracy. It is necessary to develop special techniques, including the design of the vacuum chamber, material joining (brazing and welding) technologies, to achieve the necessary vacuum levels in accelerators.

All used materials used in the UHV system must have low vapor pressure, i.e. lower outgassing levels [15, 16]. The requirements for a UHV system design can be divided into two main stages. In the first stage the requirements refer to accelerators, specifically, the beam parameters (i.e. the influence of the beam on the vacuum chamber), the specifications of the electromagnetic devices, especially the electromagnetic influences on the vacuum chambers. The second stage of requirements refers to the UHV conditions, mechanical and thermal properties, etc. These kinds of requirements are important for a more flexible and reliable operation of vacuum system.

Only the combination of all the requirements on vacuum systems can give a possibility to achieve high quality beam parameters in particle accelerators.

The vacuum systems can be divided into two main subunits - the pumping system and the vacuum chamber. The big vacuum chamber of particle accelerator is divided into many subsections. Each subsection consists of many parts and items (vacuum pumps, vacuum gauges, etc.). There are many technologies to fix, join and assemble the various vacuum sections, e.g. mechanical fastening, welding and brazing techniques.

Some of the crucial points of UHV systems are the choice of the materials used in the constructing the vacuum systems, and the various ways of connecting the materials. Particularly, in particle accelerators one often uses high quality joints between similar and dissimilar materials. One of the most interesting and challenging areas is the production of vacuum-tight joints. There are many types of such vacuum tight joints. Depending on the chosen type and the manufacturing techniques of such joints, one can significantly increase the quality and efficiency of devices, systems and subsystems.

One of the types of vacuum-tight joints is the vacuum-tight ceramic-metal joint [17, 18, 19]. There are very high requirements presented to the fabrication and operation of vacuum-tight ceramic-metal joints. The ceramic materials are brittle, light, strong and ideal electrical and thermal insulators. Based on these properties, the ceramics are widely used in UHV systems of particle accelerators. As compared to ceramics, the metals have higher mechanical strength, are non-brittle, have higher electrical and thermal conductivity, etc.

The corresponding physical-mechanical properties of materials, joint specifications and the chambers give the possibility to achieve the desirable UHV conditions and to realize an effective operation of particle accelerators.

There are many non-standard ceramic-metal joints that are widely used in particle accelerators. For the fabrication of these joints, it is necessary to develop and design special technologies to satisfy all necessary requirements.

The bonding technologies of ceramics to metals are complicated physical-chemical processes and only the combination of experimental research and the results of theoretical calculations can give the possibility to design and fabricate ceramic-metal joints with corresponding characteristics, including the necessary level of vacuum tightness, outgassing level, mechanical strength, durability, reliability, electrical and magnetic characteristics, etc.

The fabrication techniques of high quality vacuum-tight ceramic-metal joints are a part of a modern research in technological sciences. The fabrication techniques of ceramic-metal joints boarders the following research areas:

- Fundamental research on physical and chemical processes that have not been fully charachterized yet;
- Modernization of the existing fabrication techniques for increasing the quality of the resulting ceramic-metal joints;
- Development and design of new bonding technologies applied for ceramic-metal joints.

One should take into account that some of the ceramic-metal joints are supposed to operate in extreme environmental conditions. For example, UHV conditions, severe temperature gradients, electro-magnetic waves, etc. Therefore it is very important to improve the quality of the existing systems and to develop new technologies for increasing the reliability, durability and the efficiency of vacuum-tight ceramic-metal joints in the vacuum systems of particle accelerators.

Another important research area is the development of non-standard ceramic-metal joints. For this kind of joints additional special design is required, including a mechanical design, thermal calculations, electro-mechanical simulations, etc. Such design, of course, should take into account the geometric shape the used bonding technique and several other factors.

The summary of thesis modernity: The success of the design and fabrication of new generation of particle accelerators mainly depends on the choice of used materials and the technologies of producing the joints. For example, AREAL (Advanced Research Accelerator Laboratory) laser driven

RF gun based linear accelerator was operated in Armenia in 2013. It provides an electron bunch with 2-5 MeV energy and 10-100 pC charge. AREAL accelerator is used within a wide class of scientific disciplines, ranging from physics and biology to chemistry and materials science. In order to install and operate a free electron laser at the AREAL accelerator, we plan to increase the beam energy up to 20-50 MeV [20, 21].

At the same time, the requirements for the main characteristics of accelerators are significantly increasing and need more precise parameters for vacuum and RF systems, accelerator structures, control and diagnostic systems and the thermoregulation system. Particularly, depending on the commissioning conditions, the metallic components and the metal-ceramic joints should satisfy very high standards. Specifically, they should have a very high mechanical strength, vacuum tightness, temperature and radiation resistance, and more.

Even though there are already many technques for manufacturing ceramic-metal joints, the improvement and modification of the above-mentioned techniques is a modern task and is very timely for the new generation of accelerators.

Purposes and the main problems of the thesis: The main purposes of this thesis were the development of new fabrication technologies for high quality vacuum-tight ceramic-metal joints and a design of systems necessary for successful commissioning of the AREAL accelerator.

Structure and volume of the thesis: The thesis consists of an introduction, 4 chapters, conclusion section and bibliography. The thesis is presented in 137 pages. It contains 94 pictures and 18 tables.

Main topics discussed in the thesis defense: The main topics provided for thesis defense are the following:

- Thermoregulation systems for electromagnetic vacuum systems of AREAL linear accelerator: thermoregulation system of the RF gun, thermoregulation system of the klystron and the cooling system for the solenoid magnet.
- Development of new methods of brazing ceramic to metal for items made of dissimilar materials and having difficult geometrical shapes.

- Development of new bonding methods for cylindrically-shaped ceramic and metal items.
- Brazing technologies for vacuum RF windows and design of RF windows.

Thesis presentations: The main results of this thesis were presented during seminars at CANDLE SRI and at several international conferences and meetings. Particularly,

- International Particle Accelerator Conferences - IPAC (IPAC2011, IPAC2014, IPAC2017),
- IV International Conference entitled as "Current Problems of Chemical Physics" (5-9 October 2015, Yerevan, Armenia),
- International Conference "Advanced Materials and Technologies" (21-23 October 2015, Tbilisi, Georgia,),
- IVESC-ICEE-2014 – International Vacuum Electron Source Conference (June 30- July 04 2014, Saint-Petersburg, Russia,),
- AREAL - International Technical Advisory Committee seminars, and more.

Publications: The main results of this thesis are published in international scientific journals, international conference journals and intellectual property agency of Armenia. This thesis is based on 11 research papers (6 scientific journals, 3 international conference papers, 2 patents).

Scientific novelty: The main novelty of this thesis is the development of new techniques of diffusion brazing and diffusion bonding. These methods are used to joint dissimilar components with complex geometric shapes. The methods rely on the pressure difference on the two sides of the items being brazed.

Practical value of the thesis: The results obtained within this thesis research are used at AREAL facility and its vacuum laboratory. Many of the results, particularly the ones related to the design, modernization and fabrication of vacuum-tight ceramic-metal joints, can also be used in areas different than accelerator science.

Moreover, part of this thesis deals with the design of a fast and precise thermoregulation and UHV systems, which have been specifically designed for CANDLE Synchrotron Research Institute. They are already installed and operational at AREAL linear accelerator.

Finally, an RF window test stand has been designed for testing brazed ceramic-metal joints, mechanical sealing techniques and more, under high vacuum, RF and high temperature influences. Needless to say, that this also can be applied outside the realm of accelerator science. We have particularly used this to investigate various brazing and bonding techniques which we then effectively used in the UHV systems of AREAL linear accelerator.

Chapter 1. This chapter is dedicated to the description of the main parameters of the UHV and thermoregulation systems of AREAL linear accelerator. The first part is dedicated to the AREAL Linear accelerator's main parameters. The second part is dedicated to the details of the design of the UHV systems of AREAL linear accelerator, including the description of the main parameters, the design specifications, the achieved vacuum levels, the choice of the used materials and their specifications, the specifications of the vacuum-tight ceramic-metal joints, the techniques of vacuum pumping, the specifications of the e-beam titanium windows.

Additionally, the main purposes, the technical properties and the general structure of the UHV test stand are described in details.

Also the detailed description of the precise and fast thermoregulation systems is given. These include the thermoregulation systems for the RF gun, the klystron and the cooling system of the solenoid magnet.

Chapter 2. The first part of this chapter is dedicated to the description of the properties of materials used for vacuum-tight ceramic-metal joints. Particularly, we have discussed their vacuum compatibility, structure stability, brazeability and weldability, electro-mechanical characteristics, surface characteristics and more. The second part of this chapter is dedicated to the review of ceramic-metal brazing technologies; their technological specifications, advantages and disadvantages, etc.

Using the technique of active brazing based on molybdenum-manganese, we have performed a brazing of alumina to copper and alumina to stainless steel, all done in a vacuum furnace. In this chapter we describe the details of the relevant experiments.

We present the results of the investigations on ceramic-metal joints based on metallurgical analyses (i.e. metallurgical microscopy).

Chapter 3. This chapter presents the new brazing and bonding techniques for ceramic-metal joints that were developed and designed at CANDLE Synchrotron Research Institute and registered at the Intellectual Property Agency of Armenia.

Particularly, we describe in detail the new diffusion brazing method that we have developed for brazing ceramic and metallic items with complex geometric shapes. This new brazing method can effectively be used for manufacturing high quality vacuum tight ceramic-metal joints.

Also, we present the new diffusion bonding method that we have developed for bonding cylindrical ceramic and metallic items.

The second part of Chapter 3 is dedicated to the discussion of the thermo-mechanical simulations of ceramic-metal joints under high temperature conditions, relevant for brazing processes in vacuum furnaces. The results of this kind of simulations are important for the processes of brazing, as well as for understanding the behavior of the vacuum-tight joints in realistic circumstances. These simulations can be used for developing new techniques for fabricating ceramic-metal joints.

Chapter 4. This chapter discusses the applications of vacuum-tight ceramic-metal joints in particle accelerators. The main focus of the chapter is the RF windows. We have described the main operational scheme and requirements for the pillbox type RF windows. This discussion includes the requirements for their structure, the usage of materials, effectiveness of the thermoregulation system and more.

We have discussed the procedure of development of brazed pillbox type vacuum RF windows. Particularly we have presented the design and fabrication techniques, including a presentation of a new diffusion brazing technque. Additionally we have described the brazing techniques applied on various kinds of ceramic discs and metallic cylindrical items.

We have designed a pillbox type vacuum RF window as a test for mechanically sealed and brazed joints, coated ceramic materials and the thermoregulation systems of RF windows.

Additionally we have carried out preliminary thermo-mechanical simulations for pillbox type RF windows assuming high temperature conditions. The intended use of these simulations is the brazing process itself. We have also described the methods of leakage detection and the thermo-mechanical testing of RF windows.

Chapter 1: AREAL Linear Accelerator: the main parameters, ultra-high vacuum system and the thermoregulation systems

1.1. Applications of the AREAL Linear accelerator for fundamental and experimental research.

The rapid development of modern science and technology demands development of various types of advanced laboratory systems. The areas of applications of such systems vary from fundamental sciences to applied areas of research, such as material science, chemistry, pharmaceutics, health care and many more. The focus of this thesis is the technical development and maintenance of the AREAL linear accelerator. The latter was designed and realized at the CANDLE synchrotron research institute (SRI) in Yerevan, Armenia (**C**enter for the **A**dvancement of **N**atural **D**iscoveries using **L**ight **E**mission), where it is currently being successfully commissioned. AREAL accelerator for **A**dvanced **R**esearch **E**lectron **A**ccelerator **L**aboratory and is a modern linear accelerator based on a laser driven RF gun [22, 23].

The AREAL project was divided into two main phases. The goal of the Phase-1 was to reach a maximum energy of 5MeV, while the energy scale for the Phase-2 will be from 20 to 50MeV, which will feature special accelerating structures and undulator system.

The main features of the AREAL linear accelerator for Phase-2 is shown in Figure. 1.1.1. [24].

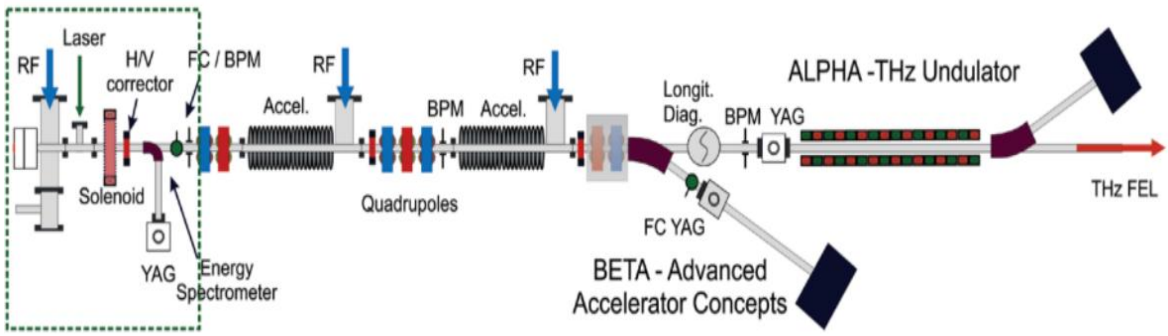


Figure 1.1.1: The main scheme of AREAL Linear accelerator.

Being a modern linear accelerator, AREAL features a large number of advanced devices, systems and subsystems, everything connected with each other. In the rest of this section we will briefly list the main systems of AREAL, before going through more detailed discussions about various aspects of these systems.

The main parameters of AREAL electron beam are summarized in Table 1.1.1.

Parameter	Value
Energy (MeV)	≤ 50
Bunch charge (pC)	10 - 250
norm (mm.mrad)ε	< 0.5
RMS bunch length (ps)	0.4 - 9
RMS energy spread (%)	< 0.15
Repetition rate (Hz)	1 - 50

Table 1.1.1.: Summary of the beam parameters.

- The so-called S-band accelerating structures are being developed and fabricated (including the mechanical design and the brazing technologies) at CANDLE SRI [25, 26], with an aim of reaching a beam energy of up to 50MeV. For that purpose a special induction vacuum brazing machine has been designed and manufactured with an application of brazing the copper fragments of the S-band accelerating structures [27].
- During Phase-2 the AREAL will be complemented with an undulator system, which is a chain of magnets with alternating polarity and is used to generate high quality coherent radiation with, in principle, tunable frequency. Such a radiation source is of direct application in many areas of modern sciences as, for example, a high quality imaging tool.
- An efficient and reliable operation of all the components of AREAL is a crucial requirement for obtaining desirable and controllable parameters of the electron beam. For that matter, two crucially important systems are the ultra-high vacuum system (abbreviated as UHV in this thesis) and the thermoregulation systems.

1.2. UHV system for AREAL linear accelerator

The UHV is one of the crucial components and is extremely important for achieving high precision electron beam parameters [28-29].

UHV system for AREAL linear accelerator has been designed and assembled at the CANDLE Synchrotron Research Institute, by carefully performing vacuum calculations and thermo-mechanical simulations. Additionally, for solving several technological problems we have developed various technical aspects, for example, new welding and brazing techniques [30]. The design of the UHV system takes into account the magnet fixation systems and the operation of experimental stations.

The 3D model of the AREAL accelerator for Phase-1 is shown in Figure 1.2.1. [31]. Note that the klystron, as well as the supporting subsystems (e.g. the thermoregulation systems) are not shown in the picture.

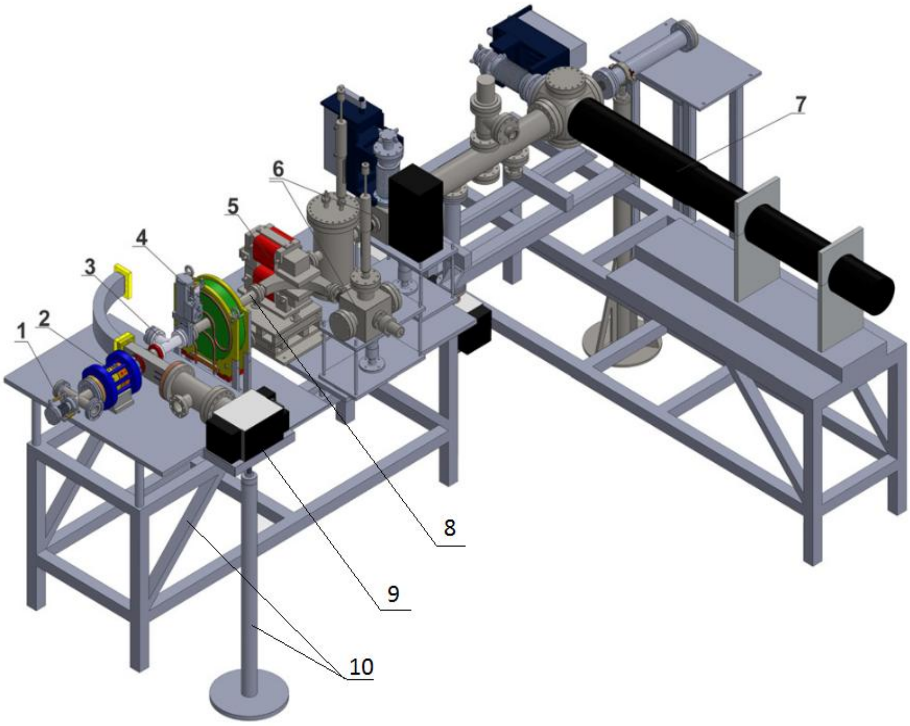


Figure 1.2.1.: 3D scheme of the machine.

The main components of the AREAL linear accelerator (Phase-1) which rely on the UHV system are (the numbering corresponds to the Figure 1.2.1):

(1) the photocathode holder system,

(2) the laser driven RF gun,

(3) the laser mirror system,

(4) the solenoid magnet,

(5) the dipole magnet,

(6) the vacuum tube with stations for beam diagnostics,

(7) the pepper pot,

(8) the beam line,

(9) the ion pump,

(10) different regulation tables, supports, fixation and alignment systems.

The 316LN stainless steel is the main construction material for the UHV system. The mentioned metal has excellent mechanical and vacuum properties (high bake-out temperature, for example), it is an austenitic steel and is a non-magnetic material [32]. The UHV pipes are made from seamless pipes of 35mm inner diameter.

We have used the so-called **T**ungsten **I**nert **G**as (TIG) welding technology for welding the stainless steel pipes to flanges (this was done in a presence of an **Ar** gas flow from the inner sides of the pipes). An orbital welding machine was used for performing the TIG welding of longer pipes.

Con**F**lat (CF) flanges have been selected with **O**xygen-**F**ree **C**opper (OFC) gaskets for sealing and all the design and fabrication processes have been done following the corresponding standards [33-36].

As a result we have achieved a vacuum level of $2.3\cdot10^{-9}$ Torr. OFC, ceramic, aluminum and several other materials were used in the UHV system of the AREAL linear accelerator.

Special mechanical procedures have been developed and used on stainless steel and **Cu** fragments of the UHV system. After mechanically processing the mentioned fragments, we have subjected these fragments to special cleaning and temperature treatment procedures with a purpose to increase their qualities.

The cleaning process has been performed in several steps. The first step was the simple, preliminary cleaning, which was followed by a special cleaning procedure in ultrasonic baths with chemical detergents and deionized water.

The final stage of the treatment was the bake-out process in high-temperature and high-vacuum conditions.

Precise and advanced vacuum pumps, vacuum measuring gauges and control systems are contained in the UHV system of the AREAL linear accelerator. Particularly, a **T**urbo **P**umping **S**tation (TPS) has been used in order to achieve a vacuum at the level of 10^{-5} to 10^{-6} Torr in the UHV chamber. After the mentioned vacuum level was achieved the shutters of TPS pumps have been closed and a further pumping was performed by using a ion pump for achieving a vacuum level of 10^{-9}Torr in the UHV chamber.

We have used ion pumps of model **Vacion Plus 75** manufactured by "Agilent". For that model the pumping speed for N_2 is 65 L/s and one can achieve a maximum level of 10^{-9} Torr vacuum. It should be mentioned that the pumping speed of ion pumps depends on the type of the gas being pumped as well as on the vacuum level [37]. Let us mention also, that in our UHV we have used inverted magnetron and hot filament ionization (Bayard-Alpert) gauges for measuring vacuum level the chamber.

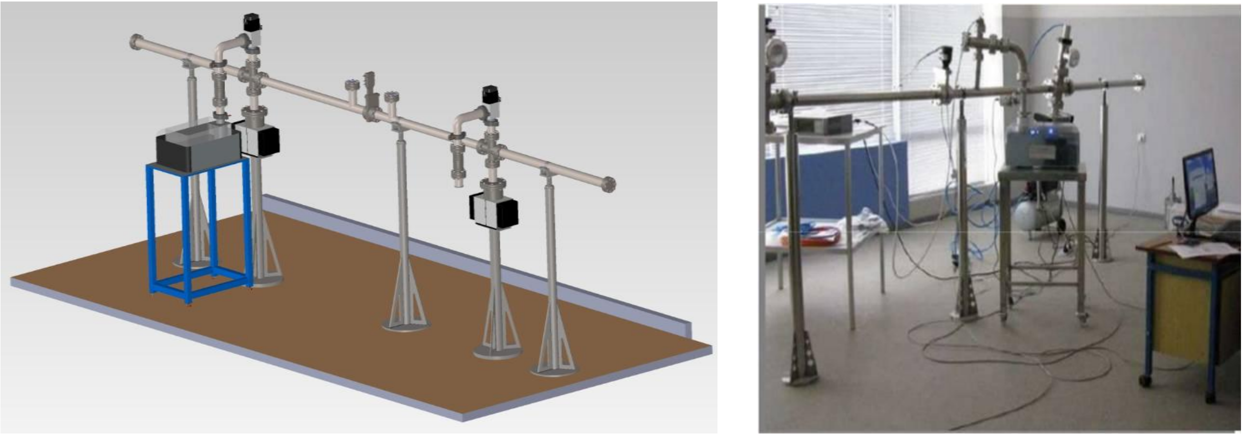
The control of the UHV system is organized from the central control room.

1.3. The UHV test stand

The UHV vacuum test stand has been designed and assembled in the Vacuum Technology Laboratory at CANDLE SRI [38]. The main purposes of UHV test stand are testing and developing the UHV systems before installing them on the main accelerator. Such tests include tests on UHV components, control systems, devices, metal-metal and metal-ceramic vacuum-tight joints, as well as bake-out temperature preparation processes of UHV components, and several more.

Figure 1.3.1 demonstrates the 3D model (left panel) and the realistic view (right panel) of the UHV vacuum test stand.

We have used the stand to test all the UHV components before installing them on the main UHV system of the AREAL accelerator, including the materials' bake-out properties, leakage detection, etc. On this stand we also have tested our brazing and welding technologies developed for vacuum-tight metal-metal and metal-ceramic junctions of the UHV systems. It is important to emphasize that such tests of the UHV components is one of the most important steps for fabricating high quality vacuum-tight junctions.



a. b.

Figure 1.3.1.: The UHV test stand.

The UHV test stand is a very flexible laboratory system and it gives possibility of wide range of tests and experiments on the UHV system components and systems under UHV and high temperature conditions.

The ion pump, **T**urbo **P**umping **S**tation (TPS), heater (external), inverted magnetron and the hot cathode vacuum gauge, as well as the alignment support and the vacuum chamber are the main components of UHV test stand. The main parameters of the stand are shown in Table 1.3.1.

Parameter	Value or Type
Vacuum level	Up to 10^{-10} Torr
Main construction material	304 stainless steel
Max. temperature	Up to 450 ^{0}C
Vacuum gauges	Inverted magnetron
	Penning
	Pirani
Vacuum pumps	Ion pumps
	Turbomolecular pump

Table 1.3.1.: Main parameters of UHV test stand.

We have chosen stainless steel of the type **304SS** as the main construction material for the test stand. A combination of a turbo pumping station (TPS) and an ion pump is used to achieve a vacuum level of up to 10^{-10} Torr. The TPS pumping station is chosen to be of model **TV81M** manufactured by “Agilent”. The latter is a reliable and effective pumping system which we have combined with a turbomolecular and scroll pumps into a single system. Both pumps are operated in an oil-free fashion.

Additionally we have used special heaters for bake-out process of the UHV components. The maximum temperature for heater is 450 ^{0}C. The bake-out temperature depends on the type of the material, its surface conditions, as well as on the required vacuum levels [39].

1.4. Titanium E-beam windows.

Some experiments in the accelerators are supposed to be implemented outside the vacuum system. We therefore need special windows for such experiments which would separate the vacuum chamber from the experimental stations. There are different types of windows for electrons, synchrotron radiation, etc. The type of windows depends on the type of the charged particle/radiation needed in a particular experiment, the particle energy, various parameters of the given experiment and so on. In AREAL we mostly use electron beam windows (E-beam windows).

There are several requirements that an E-beam window should satisfy. First of all, obviously, these windows should be vacuum-tight and not allow leakage of air into the vacuum system, they should be resistant to severe radiation conditions and be transparent enough for the electron [40].

We have chosen titanium (Ti) to be the material for the E-beam windows of AREAL linear accelerator, which is justified by the high level of transparency for e-beam and by the high mechanical strength. Thinner the titanium foil which the window is made of, more transparent it is for the electron beam. The thickness of the foil, however, is limited by its mechanical strength.

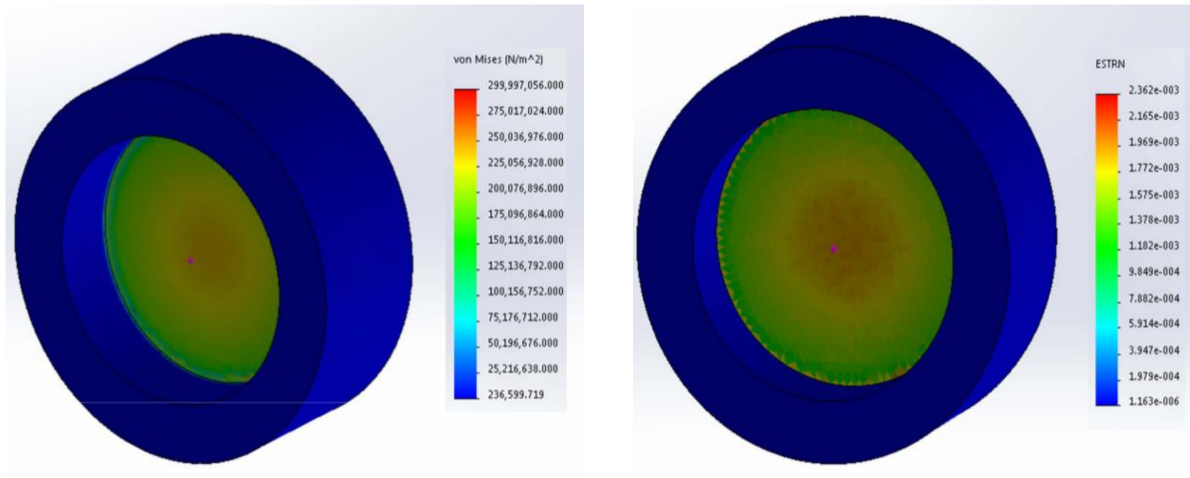
The e-beam windows are supposed to separate the atmospheric side with an average pressure of 760Torr from the UHV side with an average pressure of 10^{-9} Torr. The minimum pressure on the titanium foil is then of order of 1Atm.

In order to study the mechanical strength of the windows we have performed mechanical simulations for titanium foils with 20µm and 50µm thicknesses, both being 35mm in diameter.

The foil with 20µm thickness and 35mm diameter can lead to problems with mechanical sealing under the pressure of 1Atm and will lead to high rate of leakage of air into the UHV system.

The mechanical simulation results for the 50µm thick foil are shown in Figure 1.4.1. The simulations have been done using the FEA (finite element analysis) method assuming 1Atm pressure and 20^{0}C temperature [41]. Such 50µm thick foil has low enough stress (a, the left panel of the figure) and strain (b, the right panel of the figure).

Based on these simulations we have used the 50µm thick titanium foil with 35mm diameter as our window. The material type of the Ti foil is Grade 2.



b. c.

Figure 1.4.1.: Simulation results for e-beam Ti window. a. stress, b. static strain.

We then have mechanically assembled two 50µm-thick titanium windows which gave us a possibility to achieve a vacuum level of 10^{-9} Torr with very low leakage rate.

The real view of an assembled Ti window in UHV system of accelerator under $2.3 \cdot 10^{-9}$ Torr vacuum is shown in Figure 1.4.2. Special flanges have been used for mechanically assembling the titanium foil into a window. Copper gaskets have been used in one side and special flat flanges have been used in the other side of the Ti foil.

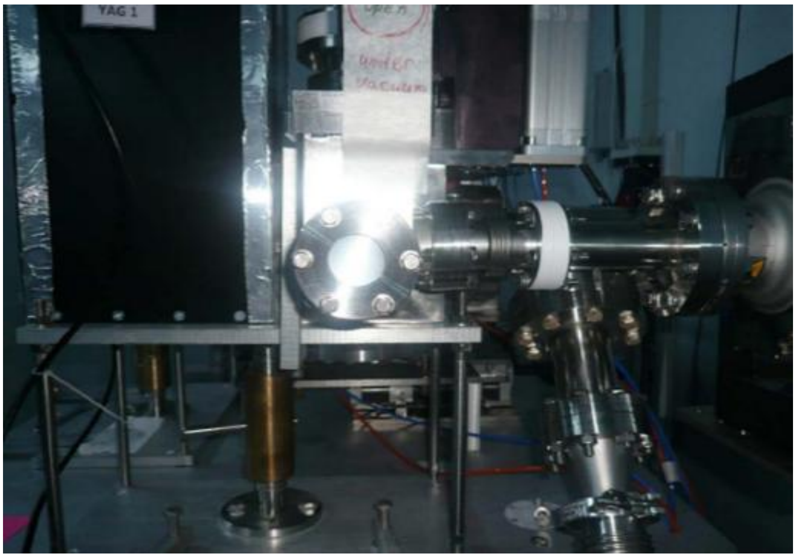


Figure 1.4.2.: The Ti window in AREAL linear accelerator under UHV conditions.

1.5. Thermoregulation systems of the AREAL linear accelerator

The thermoregulation system is yet another very important component of a modern accelerator. Each technical system of the AREAL accelerator has its own individual thermoregulation requirements.

Parameters	RF gun	Klystron		Solenoid magnet
		Resonator	Magnet	
Cooling capacity (W)	300	500-1500		2000
Temperature	30-55	30-55		15-40
Temp. stability (^{0}C)	+/-0.1	+/-0.5	+/-0.1	+/-1
Water flow rate (l/min)	11	3.64	20.5	2-30
Pressure (kg/cm^2)	<4.2	<4.2		1.5-3
Coolant	Deionized water	Distilled water		Demineralised water
Deionization level (MΩ·cm)	5.6	50 MΩ·cm		50 MΩ·cm

Table 1.5.1: The main cooling requirements of the AREAL components.

The RF gun, klystron and the solenoid magnets require fast and precise thermoregulation already at the Phase-1 of AREAL. We summarize the main thermoregulation requirements of the RF gun, klystron and solenoid magnets in Table 1.5.1.

Figure 1.5.1 shows the schematic view of the thermoregulation systems of AREAL, where the numbering is as follows:

(1) thermoregulation system for the RF gun,

(2) the cooling system for the solenoid magnet,

(3) the thermoregulation system of the Klystron,

(4) the klystron itself,

(5) the linear accelerator,

(6) the feeding water pipes for the RF gun and the solenoid magnets.

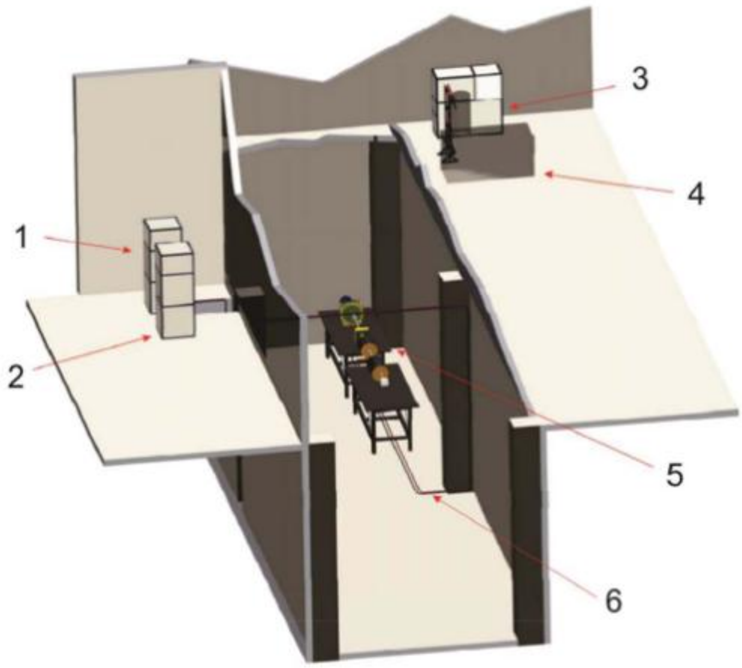


Figure 1.5.1.: Thermoregulation system's layout in AREAL Laboratory.

1.5.1. Materials for thermoregulation systems

There are various kinds of materials that are being widely used in thermoregulation systems. Each type of thermoregulation system has its special requirements for construction and the choice of materials.

Deionized and distilled water has been selected as a coolant for the thermoregulation systems of AREAL. This choice is based on the following general properties:

- it is not corrosive to the components of the thermoregulation system,
- it is chemically inert,
- it is reliable during long periods of time,
- it has low electrical and magnetic activity.

We have also used stainless steel (of type 304SS), copper, bronze and special types of plastics at various segments of the thermoregulation system.

1.5.2. Thermoregulation system of the RF gun

Thermoregulation system of the RF gun has been designed and assembled based on several technical requirements. The hydraulic scheme of the thermoregulation system of the RF gun is shown in Figure 1.5.2.1.

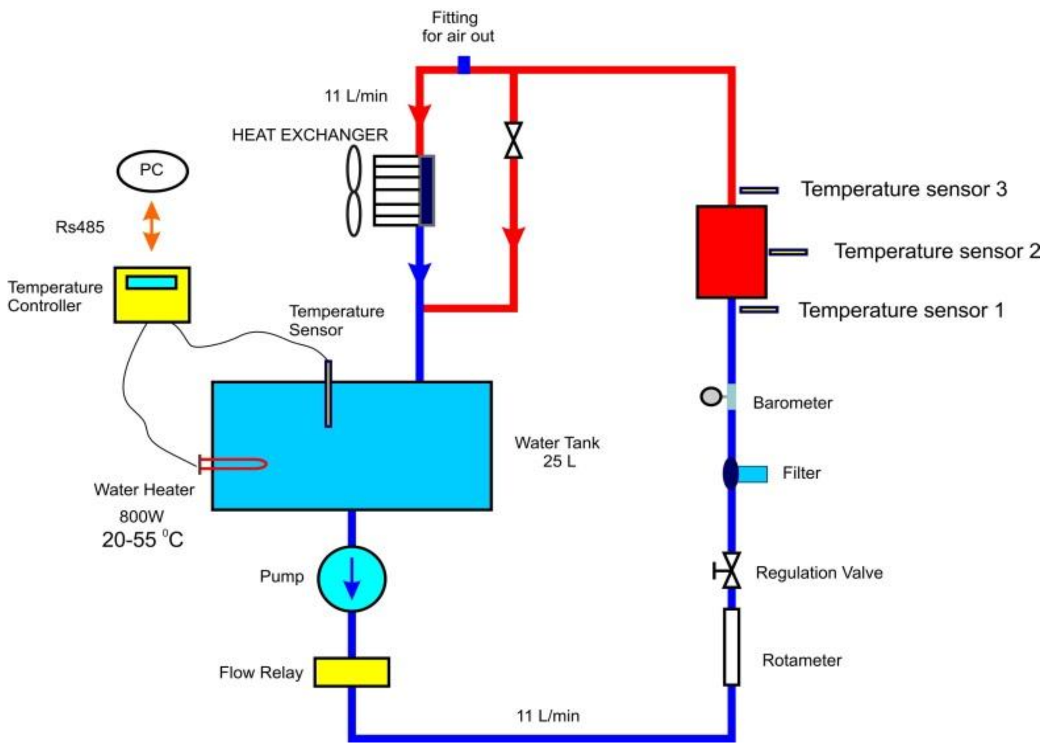


Figure 1.5.2.1: Thermoregulation system-circuit for RF gun.

For this thermoregulation system we have used deionized water with a minimum of 5.6MΩ·cm electrical resistance. Stainless steel, braze, copper and special plastic materials have also been selected for circuit system.

This thermoregulation system has an electrical heater with 800W power. The fan heat-exchanger is being used cooling down the water. The effective operational temperature of the RF gun is approximately 37.5 ^{0}C. One of the important parameters of the thermoregulation system is the level of temperature stability, which is required to be quite high. The thermoregulation system of the RF gun is a very fast and quite precise system and is able to provide a temperature accuracy of +/-0.1^{0}C.

Figure 1.5.2.2 demonstrates the realistic view of the thermoregulation system of the laser driven RF gun [42]. Its main technical parameters are summarized in Table 1.5.2.2.

As one can see from the Table 1.5.2.2, the maximum cooling capacity is 500W, while the required cooling capacity for the RF gun is approximately 300W. The thermoregulation system is providing a laminar water flow rate in water circuits based on special scheme. The effective working temperature of the RF gun was obtained experimentally.

Figure 1.5.2.2: Thermoregulation system for RF gun.

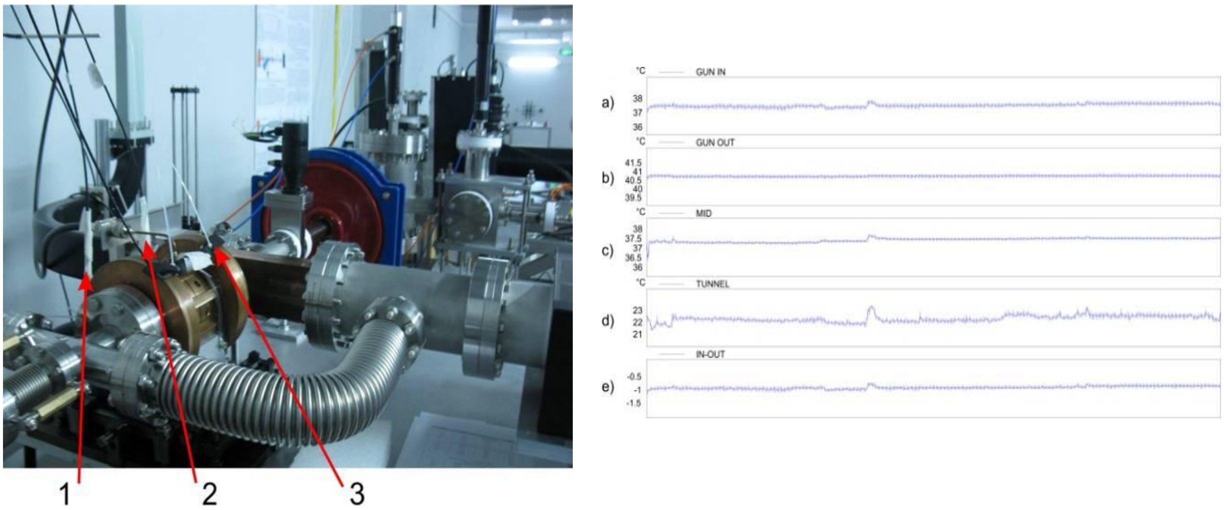
Characteristics	Value
Cooling capacity (W)	500
Temperature range (^{0}C)	30-55
Temperature stability (^{0}C)	+/-0.1
Water flow rate (l/min)	2-15
Pressure	Not exceed 4.2kg/cm^2
Coolant	De-ionized water
De-ionization level	5.6 MΩ·cm

Table 1.5.2.2: Main technical parameters of thermoregulation system of RF gun.

This thermoregulation system of the RF gun is a reliable and flexible system and can be controlled both locally and remotely, from the central control room.

Proportional-**i**ntegral–**d**erivative (PID) controllers of type DTD4848 manufactured by “Delta” are being used for the temperature control.

Platinum sensors of the type Pt100 (Platinum resistance thermometers) have been used for the temperature measurement and regulation. Pt100 sensors have 100Ω resistance at 0^{0}C temperature and the temperature range measured with these sensors is from 200 to 600^{0}C.



a. b.

Figure 1.5.2.3: a. Temperature sensors fixations on the gun, b. measurements results.

The PID controller has an RS485 input connection which gives a possibility to regulate it from the control room.

The temperature sensor is fixed within the inner volume of the water tank. Pt100 probe has a stainless steel body and can operate without contamination of water quality. Additionally, three precise and sensitive temperature sensors (SE012) are used to measure the temperature of the RF gun.

The positioning of the temperature sensors on the RF gun is shown in Figure 1.5.2.3.a, where the numbers represent the following

1. a temperature sensor on the water flow entering the gun,
2. a temperature sensor on the water flow exiting the gun,
3. a sensor located at the center of the gun.

A set of typical results of the temperature measurements is shown in Figure 1.5.2.3.b.

SE012 temperature probes are very reliable and precise sensors with measuring range between -50^{0}C to 250 ^{0}C and with an accuracy of 0.03 ^{0}C.

We have performed measurements at the real operational conditions of AREAL, the measurement accuracy of the temperature of the RF gun is approximately +/-0.1 ^{0}C. In the right panel of Figure 1.5.2.3 we show a part of the temperature measurements

- at the gun entrance (a),
- at the gun exit (b),
- at the middle point (c),
- the tunnel temperature (d),
- the in-out difference (e).

All these measurements are recorded in the control room. As it is seen from the above mentioned figure, the thermoregulation system provides a temperature stability at the gun entrance of 37.5 ^{0}C with an accuracy of +/-0.1^{0}C.

The in-out temperature difference for the gun is about 1.5^{0}C. Figure 1.5.2.3 -b(d) shows the stability of the air temperature at the accelerator tunnel which is kept at 22.7^{0}C. For the temperature measurements in the RF gun we have used a Pt104 data logger. The latter has many advantages, particularly, it has a high resolution and a high accuracy, it is compatible with PT100 and PT1000 sensors, supports 2, 3 and 4-wire sensors, does not require a power supply, has USB and Ethernet interfaces, can run multiple units on a single PC. The main technical parameters of the Pt104 data logger are shown in Table 1.5.2.3.

Considering the thermal requirements of the electron gun, as a coolant we have used deionized water with 5.6 MΩ·cm of nominal specific resistance. All materials used in the thermoregulation system are chosen based on high purification level requirements and also are non-corrosive materials.

The thermoregulation system of the RF gun is located 3.5 meters above the electron gun, in the area of the cooling systems.

The main technical problem of the thermoregulation system of the RF gun is that the water purity decreases during time. The main influence on the specific resistance of de-ionized water is caused by the corrosion of the cooling system's components. For the efficient and reliable operation, the cleaning of the gun's thermoregulation system before the inlet of the deionized water is very important. To maintain the water purification level during long time-scales, the hoses of the thermoregulation system are changed by plastic pipes.

Type	Temperature	Resistance	Voltage
Sensor	PT100, PT1000	n/a	n/a
Temperature coefficient	5ppm/^{0}C	5ppm/^{0}C	100ppm/^{0}C
Resolution	0.001 ^{0}C	1μΩ	0.156 μV
Number of inputs	4		
Converter resolution	24bits		
Output connectors	USB and Ethernet		
Probe type	SE012		
Temperature range	-50 to 250^{0}C		
Accuracy	+/-0.03^{0}C @ 0^{0}C		

Table 1.5.2.3 : Main parameters of Pt104.

The main characteristics of SE012 probe are shown in Table 1.5.2.4.

Probe type	SE012
Temperature range	-50 to +250 0C
Accuracy	+/-0.03 0C @ 0 0C
Dimensions (length, diameter, cable)	150/4/2
Material	Stainless steel probe, PTFE cable
Handle	No

Table 1.5.2.4.: Main parameters of SE012 sensor.

The thermoregulation system of the photo injection gun consists of a heat exchanger (which is a fan made of copper), water tank (made of stainless steel), water pump (body and the inner structures are made of stainless steel), metal-plastic pipes, controlling valves, control system, water flow relay, rotameter, barometer.

1.5.3. Thermoregulation System of the RF Klystron

The thermoregulation system of the RF klystron is one of the important thermoregulation systems of the AREAL accelerator. At the CANDLE SRI we have designed and assembled such a thermoregulation system, including the design of the hydraulic scheme, the thermo-mechanical calculations, mechanical design, drafting, electronic control system, technical manufacturing, assembling and testing [43]. The hydraulic scheme of the klystron's thermoregulation system is shown in Figure 1.5.3.1, while Figure 1.5.3.2 shows its realistic view. This system is located near the klystron itself, in the RF laboratory.

Table 1.5.3.1 summarizes the main technical parameters of the klystron's thermoregulation system [44].

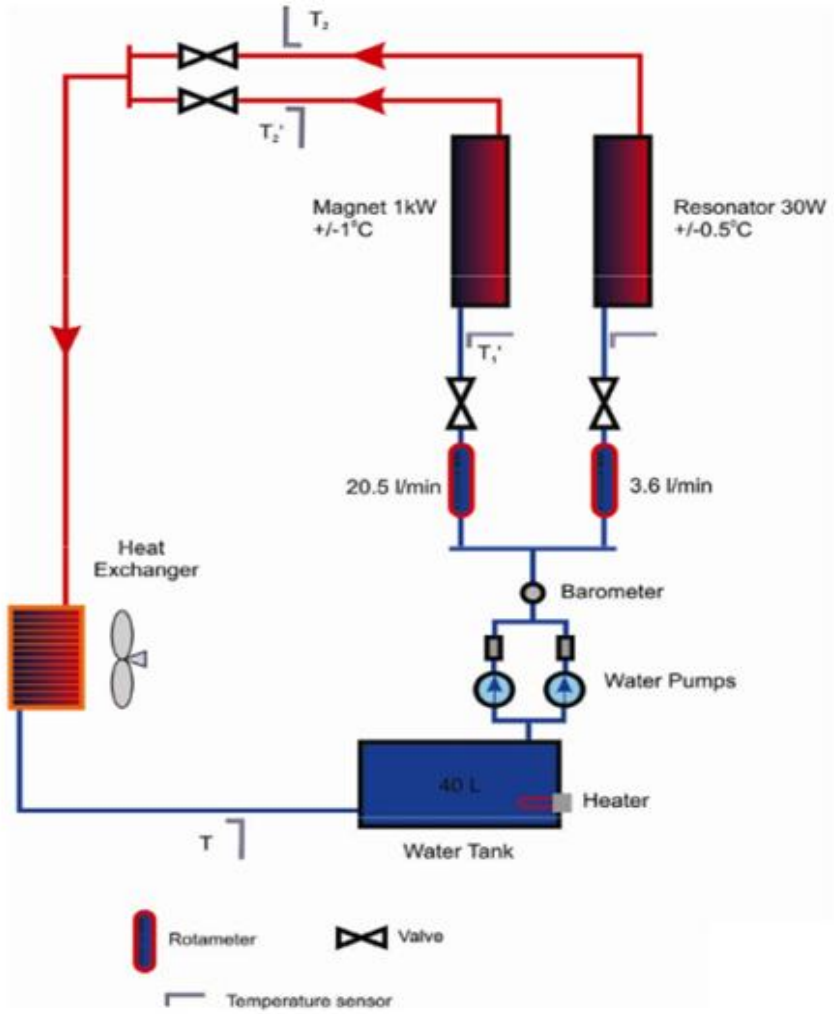


Figure 1.5.3.1.: Hydraulic scheme of thermoregulation system of RF klystron.

Distilled water is used as a coolant in the thermoregulation system of klystron. Stainless steel, copper, bronze and special plastics are used as construction materials in the water circuit system. A high purification level of distilled water can be kept for quite a long time. The period for changing the distilled water is approximately 1400 hours. Before inletting new water, the system is being cleaned by distilled water.

Figure 1.5.3.2.: Realistic view of klystron's thermoregulation system.

The thermoregulation system is divided into three main sections (see Fig. 1.5.3.2), namely, the water tank section (40 L), the heat exchanger section (Cu heat exchanger with fan) and the water pump section.

Characteristics	**Value**	
	Resonator	**Magnet**
Cooling capacity (W)	500-1500	
Temperature range	30-55	
Temperature stability ^{0}C	+/-0.5	+/-1
Water flow rate (l/min)	3.64	20.5
Pressure (kg/cm^{2})	<4.2	
Temperature sensor	Pt100	
Coolant	Distilled water	
Water deionization range	50M Ω·cm	
Nominal pressure (bar)	3.3	

Table 1.5.3.1: Main technical parameters of the cooling system.

The main components of the klystron's thermoregulation system are the heat exchanger, the water tank, rotameters, pressure relays, pressure measurement sensors, temperature regulators, special water filters, temperature measurement sensors, heater, water pumps, metal plastic pipes.

We have used PID controllers with Pt100 sensors (platinum resistance thermometer) as our temperature regulators. The Pt100 sensors are immersed into the water tank.

The thermoregulation pipes of the klystron are divided into two parts, the resonator and the magnet, both having different water flow requirements. The working temperature is the same for both the magnet and resonator sections, but water flow rates are different. Near the klystron the collector divides the water flow into the resonator and the magnet.

We have used two water pumps, one of them being in the operational mode and the other one serving as a reserve pump. These are of the type SAER M99 and the range of the working temperature ranges from -10 to +50 ^{0}C.

The thermoregulation system is controlled from the control room. All components, subsystems and junctions of the thermoregulation system are tested in laboratory conditions before the final assembling in the main system.

1.5.4. Cooling system for the solenoid magnet

We have also designed (including the thermo-mechanical design and the design of the control system) and assembled the cooling system of the solenoid magnet. The main parameters of this cooling system are presented in Table 1.5.4.1. Here, as a coolant we have used demineralised water. Additionally, DTA 4848-type PID temperature controllers have been used together with Pt100 temperature sensors.

The use of PID controllers gives a possibility to flexibly and efficiently regulate the temperature of the circulating water. The heat exchanger consists of a fan and copper pipes. The heat load is increased by increasing the electrical current in the solenoid magnet.

This system is used only for cooling and for the temperature regulation we are regulating the water flow rate and the fan speed. Additionally the system has an inner mechanical filter. It is necessary to periodically change the filter and input new clean water into the system. In order to increase the purity level of the water it is necessary to keep the water in circulation. The circulating water can be kept pure during a sufficiently long time.

Characteristics	Value
Temperature range	20-40 ^{0}C
Temperature stability	+/-1 ^{0}C
Temperature sensor type	Pt100
Temperature regulation type	PID
Coolant	Demineralized water
Water deionization range Ω·cm	50 Ω·cm
Cooling capacity	2’000 W
Nominal pressure (bar)	3.3
Water flow rate	2-30 l/min

Table 1.5.4.1.: Main technical parameters of solenoid cooling system.

The cooling system is operational at the temperature range of 20 to 40 ^{0}C (the temperature of the water), which depends on the electrical current flowing in the solenoid magnet.

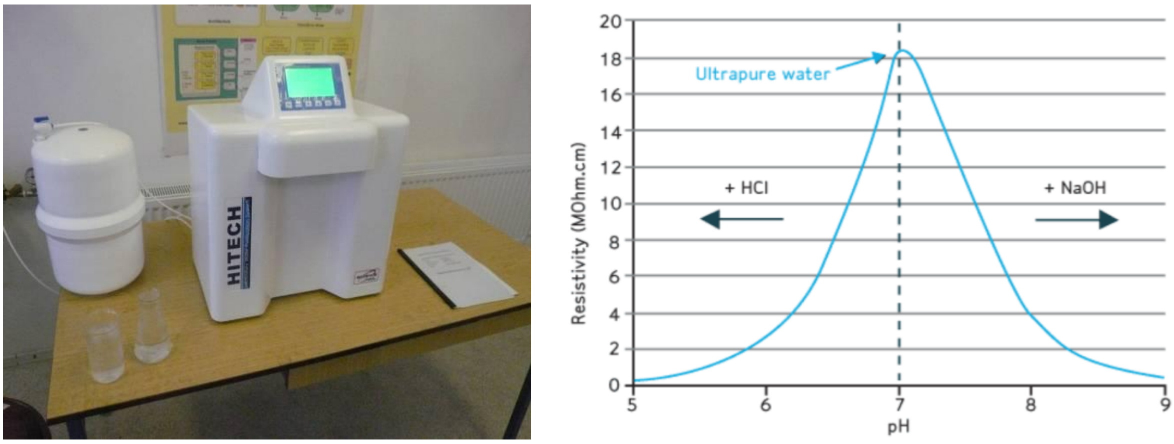
1.6. Water Purification Systems

As mentioned above, the ultra-pure deionised water is being used within the thermoregulation systems of AREAL (particularly in the RF gun).

The water purification level is a very important property for the efficient operation of the electromagnetic devices and systems of the accelerators [45 - 48]. Deionised water is a particularly ideal coolant for electromagnetic equipment for the following reasons:

- low ionization level,
- low electrical conductivity,
- high purity,
- high heat capacity, etc.

The left panel of Figure 1.6.1 demonstrates the water deionizer (a) and the right panel (b) demonstrates the dependence of the resistance of the purified water on the pH level. Ultra-pure water loses its high purity level when in contact with air.



a. b.

Figure 1.6.1.: a. The water deioniser. b. Specific resistance vs. pH level.

At the CANDLE SRI we have set up a small laboratory for obtaining and diagnosing purified water. We have used Master-Q type deionisers for purifying the water, as well as an electric conductivity meter for measuring the properties of the obtained water. Special containers and pipes were used for storing and transporting the deionised water (see below for a discussion).

Water distillers have been used for achieving demineralization and distillation of the water used in the solenoid magnet's cooling system and several other purposes. Deionised and distilled water is used for cleaning the UHV components and systems, as well as for different laboratory experiments.

It is important to know that deionised water can easily be contaminated during a short contact with air. CO_2, O_2 and many other components from air can easily cause a significant contamination. For avoiding such a contamination it is necessary to keep the deionised water in special containers insulated from air and stored in a special closed supply system.

One of the characteristics of deionised water is pH level. For maximum ultra pure water the pH level is 7 [49]. If pH level is lower than 7 that the liquid is acid. If pH level is higher than 7 in that case the liquid is bases.

For measuring the quality of water are used SanXin SX650 conductometer. SanXin SX650 can measure of TDS (Total Dissolved Solids), EC (Electrical Conductivity), Salinity meter and resistance.

Special technological sequences for receiving, keeping, moving and measuring of quality of deionised and distilled water are created.

The measurement of the resistance of water are presented. Special calibration are required for conductometer for precise measuring – ideally it will calibration before each measurements. Before measurements is necessary to clean the detectors of electrical conductor meter by deionised water.

The thermoregulation systems have special fitting for inlet and outlet of deionised water. During time are changing the water from thermoregulation systems. Before inlet new high purified water (deionised water) the all pipes of thermoregulation systems are cleaned.
Contamination level of deionised water during time in thermoregulation systems are depends on several reasons – materials of water circuits, quality level of inlet water, temperature, contact with air, water flow velocity, electrical and galvanic potential differences, etc. Each reason is related to each other.

The combination of corresponding materials and ultra pure water (deionised water) corresponding technological scheme (measuring, receiving, cleaning, transporting of water, etc.) are give possibility to implement of effective and reliable thermoregulation in the electromagnetic devices and systems of particle accelerators.

1.7. Vacuum-tight metal-ceramic joints in AREAL linear accelerator

As already mentioned above, the UHV system of the AREAL linear accelerator is a complicated system consisting of a large number of subcomponents, which rely on technically complicated methods of joining different types of materials together.

One of the interesting and technologically challenging types of joints in the vacuum system is the ceramic-to-metal joint. Such joints are contained in the klystron, the vacuum window of the RF, the beamline insulators, the vacuum breaks, the vacuum feedtroughs and more. Below we list more details on these components.

- **Klystron** – The klystron is a vacuum tube for generating electromagnetic waves which are transferred to the accelerating structures. Naturally, reliable vacuum-tight ceramic-metal joints are very important for klystrons and the quality of such joints determines the efficiency and quality of the beam acceleration. The vacuum-tight ceramic-metal joints are used in klystrons as high-voltage insulators, output RF windows, cathode holders and more. Such ceramic-to-metal joints in klystrons are technically very challenging to realize, given the fact that they should be operational in extremely low pressure conditions (in UHV), being subject to the influence of severe electromagnetic waves. Additional difficulties arise because of the changes in the temperature conditions, the presence of mechanical stress, etc.
- **RF window –** RF windows are used to separate the UHV system from the waveguide. These RF windows are transparent for electromagnetic waves. There are several types of such windows. The main construction materials of the RF windows are metals and dielectric materials such as different kinds of ceramic materials - alumina, beryllia, etc. For the RF windows it is particularly difficult to make vacuum-tight ceramic-metal joints.
- **Beamline insulators, vacuum breaks** - The vacuum breaks are very important vacuum-tight ceramic-metal joints and are widely used in UHV systems of particle accelerators for electrically insulating two metallic sections of the UHV from one another. The beamline insulators must have the same diameter as the diameter of the beam pipe.
- ***Vacuum feedthroughs*** – The vacuum feedthroughs are used for inputting and outputting electricity (or electrical impulses) to or from the vacuum system. Particularly they are used for reading the data from different gauges (Bayard-Alperd gauges, magnetron gauges, gauges of the diagnostic systems, etc.).

1.8. The summary of the Chapter 1

- Fast and precise thermoregulation systems have been designed and assembled for an effective and reliable operation of electromagnetic vacuum systems of AREAL linear accelerator. These include the thermoregulation system of the RF gun, the thermoregulation system of the klystron and the cooling system of the solenoid magnet. These thermoregulation systems are able to provide a temperature control with up to +/-0.5^{0}C accuracy.

- An UHV test stand has been designed and assembled for testing and investigating the components of the UHV system, as well as the metal-metal and metal-ceramic junctions in the UHV.

- An UHV system has been designed and assembled for an effective operation of electro-magnetic systems of AREAL linear accelerator.

Chapter 2. Experimental investigation of ceramic-metal brazing technologies for UHV systems

2.1. Technical requirements for vacuum-tight ceramic-metal joints

Vacuum-tight ceramic-metal joints are widely used in many subsystems of modern particle accelerators. These include the vacuum RF windows, insulator-breaks, kicker magnet chambers, vacuum feedthroughs, etc. The manufacturing process of such joints is associated with several technological challenges (mechanical treatment, special brazing, welding, testing, etc.). An additional challenge is the severe operational conditions of the components containing such joints (high levels of vacuum, severe electromagnetic, thermal and mechanical effects, etc.) [51].

The correct choice of the fabrication methods is a key for the effective and reliable operation of vacuum-tight ceramic-metal joints. One of the crucial aspects of fabrication technologies of the joints made of dissimilar materials is the methodology of materials bonding, i.e. vacuum brazing, welding techniques, etc. [52].

There are several very important requirements that the vacuum-tight joints should satisfy. Here are the most important ones:

- high mechanical strength over a wide range of temperatures,
- thermal shock resistance (endurance through numerous thermal cycles),
- low outgassing levels,
- low level of transparency for gasses and vapors (H_2, Ar, N_2, H_2O, etc.),
- suitable electromagnetic properties,
- high level of reliability and durability.

These requirements vary depending on the particular operational conditions where the joints are being used. In any case, the requirements always are at very high level one should very carefully keep all the technological sequences and quality control procedures [53].

The material selection is the first crucial steps of the designing process [54]. The range of possibly applicable materials is in principle quite wide, but a particular application restricts this range severely.

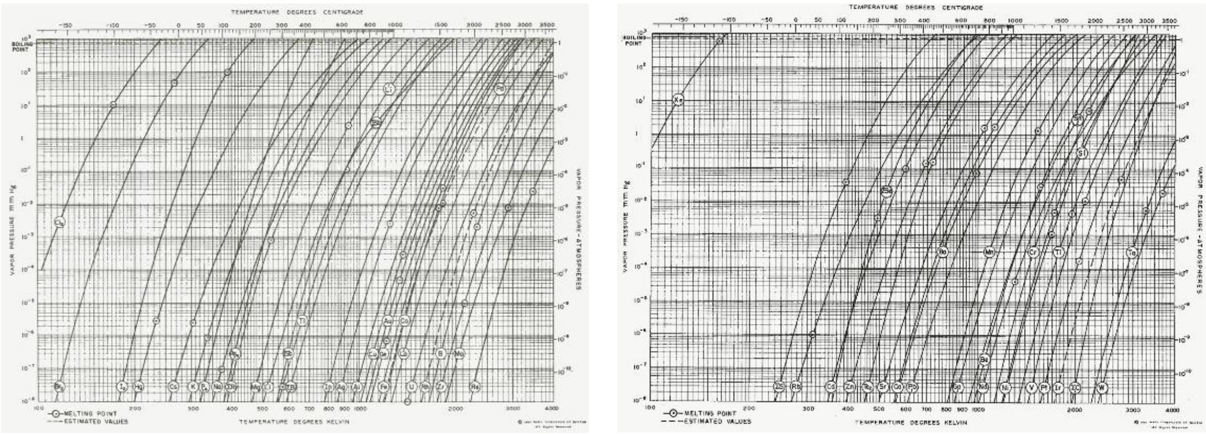
2.2. Properties of materials for vacuum-tight ceramic-metal joints

The main properties of the materials used in vacuum-tight ceramic-metal joints are listed below:

- compatibility with very low-pressure vacuum,
- structure stability,
- brazeability and weldability,
- electromagnetic properties,
- mechanical properties,
- properties of thermal expansion,
- homogeneity,
- surface properties.

Ceramics and all metals for UHV acceleration systems must be compatible with UHV conditions [55]. All vacuum materials must have low vapor pressure in order to maintain a low outgassing level [56 - 59].

The dependence of the value of vapor pressure on the vacuum level and the temperature for several metals is shown in Figure 2.2.1 [60]. Such metals as Cd, Zn, Cs and Hg have significant vapor pressure and these metals are unacceptable for UHV systems because of the mentioned high level of outgassing. In the UHV system it is important to use materials as clean as possible, meaning they should have low gassing levels, should not contain any large cracks, bubbles, sticking and other impurity layers. Special cleaning and bake-out technologies are require for similar and dissimilar joints [61-64].



a. b.

Figure 2.2.1: Vapor pressure for several metals.

The outgassing rates of several materials kept in vacuum for one hour at the room temperature are shown in Table 2.2.1 [65]. Bake-out process of materials gives a possibility to significantly reduce the outgassing rate. Aluminum has one of the lowest outgassing rates given that it has been baked-out for 20 hours at the temperature of 100 ^{0}C (see Table 2.2.1).

Material	K_1 (mbar l s^{-1} cm^{-2})
Aluminum (fresh)	9×10^{-9}
Aluminum (20 h at 100 ^{0}C)	5×10^{-14}
Stainless steel (304)	2×10^{-8}
Stainless steel (304, electropolished)	6×10^{-9}
Stainless steel (304, mechanically polished)	2×10^{-9}
Stainless steel (304, electropolished, 30h at 250 ^{0}C	4×10^{-12}
Perbunan	5×10^{-6}
Pyrex	1×10^{-8}
Tefon	8×10^{-8}
Viton A (fresh)	2×10^{-6}

Table 2.2.1.: Approximate outgassing rates of common metals.

Another important aspect is the low level of permeation for different gases.

We would like to emphasize that all the selected materials in the various joint structures must have very high level of structure stability over a long period of time and wide range of temperatures, as well as mechanical, electromagnetic and chemical conditions [66]. The brazeability and weldability of materials are yet other very important and crucial properties for making the effective bonding of ceramics to metals possible [67].

a. b.

Figure 2.2.2. Contact angle.

Some materials are compatible for brazing and welding, and some materials are incompatible. One of the estimates of material's compatibility is the contact angle or the wetting level.

If the contact angle of materials is low (exactly 0^o or nearly 0^o) the wetting is (almost) perfect and the material's contact area is larger (Figure 2.2.2.-a). If the contact angle is larger (near 180^o) then the materials do not have large enough contact area (Figure 2.2.2-b).

ANSI Grade	C max	Si max	Mn max	S max	P max	Ni	Cr	Mo max	N max
316	0.08	1.0	2.0	0.045	0.03	10.0-14.0	16.0-18.0	2.0-3.0	-
316L	0.03	1.0	2.0	0.045	0.03	10.0-14.0	16.0-18.0	1.2-2.75	-
316LN	0.03	1.0	2.0	0.045	0.03	10.5-14.5	16.5-18.5	2.0-3.0	0.12-0.22
310S	0.08	1.2	2.0	0.045	0.03	19.0-22.0	24.0-26.0	-	-
304	0.08	1.0	2.0	0.045	0.03	8.0-10.5	18.0	-	-
304N	0.08	1.0	2.0	0.045	0.03	8.0-10.5	18.0-20.0	-	0.1-0.16

Table 2.2.2: Main properties of stainless steels.

The wettability level depends on the material's chemical composition, its crystalline structure, the temperature, the level of cleanness of the surfaces, roughness, and in some cases also on the pressure.

Many components in the accelerator are built from stainless steel and copper, which are vacuum-compatible, effective and quite cheap materials. There are especially widely used in the UHV systems. There are many types of stainless steels, particularly, the austenitic stainless steels is a non-magnetic metal, hence very suitable for accelerator technologies. The types and contents of austenitic stainless steels are tabulated in Table 2.2.2. One can see from the table that the stainless steel of the kind 316LN has comparably low magnetic properties, which is explained by its special contents (0.12 - 0.22% of N and 2 - 3% of Mo). The 316LN-type steel has very good mechanical and vacuum properties, i.e. it has low outgassing level, high bake-out temperature, etc. Due to its low magnetic properties this particular type of stainless steel is very widely used in modern accelerators (especially in their UHV systems). The main drawback is its higher price compared with other types of austenitic stainless steel [70].

	Unit	BeO	Al2O3	AlN	F99.7	Fused quartz
		Beryllia	Aluminium oxide		>99.5% Al_2O_3	SiO_2
Density	g cm^{-3}	3.0	3.987	3.26	3.9	2.203
Melting point	°C	2510	2,072	2200	~2070	1650
Thermal conductivity	W/(m·K)-20^0C	330	30	140-180	34.9	1.3
Specific heat capacity (C)	J/mol K	25.5	67.24	30.1		45.3
Coefficient of thermal expansion	10^{-6} K^{-1}	9.3 (0-1400^0C)	4.5		3.6	5.5×10−7/°C
Hardness	Mohs scale	9	9	7		5.3–6.5
Compression strength	MPa	2400	2100	2100	3500	>1.1 GPa
Bending strength	MPa	185-200	>450	>350	350	
Dielectric strength	kV/mm (50^0C)	13.8	40-400	17	>30	30
Electrical Resistivity	Ω•cm	10^{15}		10^{14}	10^{15}	10^{18}

Table 2.2.3: The main characteristics of some UHV ceramics.

The dependence of magnetic properties on temperature for materials is a very important specification for effective and safe operation of brazed and welded joints. In many subsystems of the accelerator, such as the beam lines and waveguides, one is forced to use non-magnetic materials [68, 69].

High mechanical properties (especially mechanical strength) are required for materials of UHV beam lines and waveguides.

		Cu	Ag	Si	W	Mo	Mn	Al	Ti	Ni
Density	g/cm^3	8.92	10.49	2.33	19.23	10.28	7.21	2.70	4.506	8.9
Melting point	^{0}C	1083.4	961	1414	3422	2623	1246	660.32	1668	1455
Thermal Conductivity	W/(m·K)	401	429	149	173	138	7.81	237	21.9	90.9
Thermal expansion	10^{-6}/K at 25^{0}C	16.5	18.9	2.6	4.5	4.8	21.7	23.1	8.6	13.4
Young's modulus	GPa	110-128	83		411	329	198	70	116	200
Hardness	Vickers MPa	343-369	251		3430-4600	1400-1740		160- 350	830-3420	638
Magnetic ordering		Diamagnetic			Paramagnetic					Ferromag

Table 2.2.4: The main characteristics of some UHV metals.

The main characteristics of materials for vacuum-tight ceramic-metal joints are presented in Table 2.2.3 (ceramics) [71- 73] and Table 2.2.4 (metals) [74, 77].

Solder	M. T. ^{0}C	Sn	Zn	In	Ag	Pd	Cu
Palcusil®10	850	-	-	-	58.5	10	31.5
Palcusil®5	814	-	-	-	58.5	5	26.5
Ag72 Cu28	780	-	-	-	72	-	28
Incusil 10	730	-	-	10	63	-	27
Cusiltin	718	10	-	-	60		30
ПСр-45	665—725	-	25.85	-	45	-	30.5
ПСр-65		-	14.1 - 15.85	-	64.5-65.5	-	19.5-20.5

Table 2.2.5: Some solders contents.

Ceramics are non-magnetic materials and for that are important component for accelerators UHV systems (kicker magnet chamber, vacuum RF window, beam line insulators, breaks, feedthroughs, etc.).

Corresponding solders types are very important for vacuum brazing processes of high quality joints. There are many types of solders. Each type of metals (joints) are required of special solders. UHV systems are limited of many solders usage (vacuum tightness, outgassing, etc.). Some solders that widely using in UHV systems are presented in Table 2.2.5.

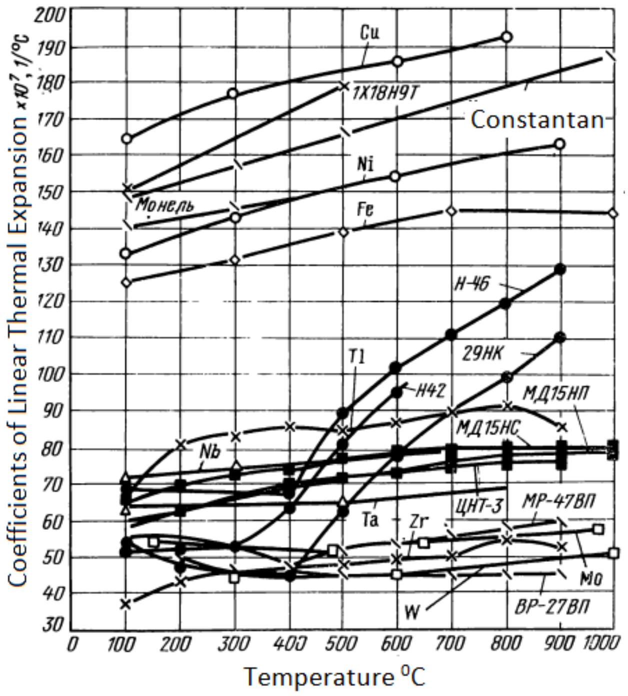


Figure. 2.2.3.: Linear thermal expansion for some materials.

Coefficient of linear thermal expansion of materials is very important properties for receiving of desirable properties [78, 79].

The dependence of linear coefficient of thermal expansion of materials on temperature is presented in Figure 2.2.3. [51].

The similar thermal expansion coefficient of brazing materials is important for effective brazing process by reducing of mechanical stresses in brazed zones dunder cooling down process.

The kovar is used in ceramic to metal brazing. The kovar has lower thermal expansion coefficient like ceramics. The content of kovar is Fe – 53.49, Ni-29, Co-17, C-0.01. The magnetic properties of kovar is the main disadvantage.

Materials homogeneity is crucial for some application of UHV system. Material homogeneity is include sub dislocations effects, cracks, emptiness and inner and outer impurities, etc. For ceramic-metal joints the materials high homogeneity is very important.

All materials which are used for vacuum-tight ceramic-metal bonding must satisfy the following main requirements:

- Reliable during long time,
- UHV compatibility (easy to clean, low outgassing rate),
- Structure stability,
- Appropriate electromechanical properties,
- Resistance to corrosion,
- Metallization characteristics.

These requirements for materials can vary depending on the desirable results of ceramic-metal joints.

2.2.1. Selection of materials

The pure and high quality materials have been selected for research and experiments considering of reviewed literature. The selected materials are alumina, stainless steel (316LN, 316L, 304, etc.), copper (OFC, normal Cu, etc.), kover, Mo, Mn, etc.

2.3. Comparison of ceramic to metal bonding technologies in UHV conditions

There are many different bonding technologies for producing vacuum-tight ceramic-metal joints. Each bonding technology has its own advantages and disadvantages. One can divide the types of ceramic to metal bonding technologies into the following main categories [80]:

- active brazing,
- brazing based on metallization of ceramics,
- thermo-compression bonding (known also as diffusion welding),
- gluing techniques,
- mechanical sealing.

Active brazing techniques are widely used in vacuum-tight ceramic-metal brazing procedures. Such technologies are technologically simpler, more flexible and cheaper compared to, for example, molybdenum-manganese technologies. These techniques are realized based on Ti and Zr active metals. The main disadvantage of this technique is the presence of intermetallic structures in the intermediate layers of the joints.

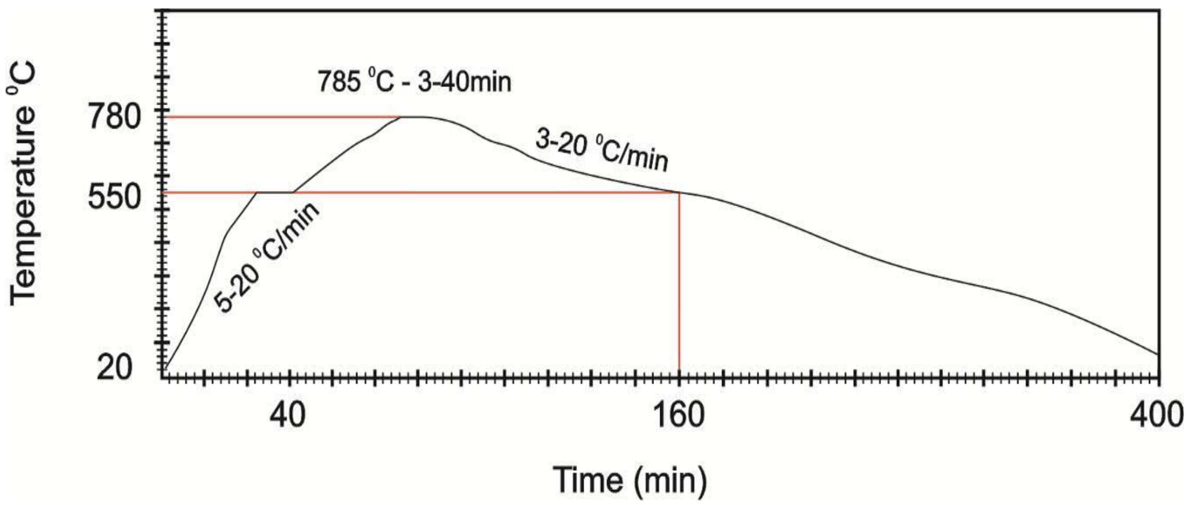


Figure 2.3.1: Brazing diagram for ceramic-metal joints.

Brazing technologies based on the procedure of metallization of ceramics are widely used for brazing ceramics to metals. A more reliable and effective method is the molybdenum-manganese metallization technique. The latter method involves several technological steps which include the metallization of the ceramic surface (i.e. covering the surface with Mo-Mn), Ni plating and soldering.

Ceramic-metal brazing technologies are very difficult technologies and require special brazing procedures. Warming up and cooling down diagram of vacuum brazing (solder type Ag72-Cu28) has been developed for ceramic-metal joints (Figure 2.3.1). Considering of differences of thermal expansion coefficient of ceramic and metal the cooling down process must be slowly at 3 to 20 ^{0}C/min. Slowly cooling down is gives possibility to reduce of mechanical stresses in contact zone of joint.

Thermo-compression bonding technology is realized under vacuum or inert gas environment, under corresponding temperature level and under corresponding force [81]. Thermo-compression bonding (diffusion welding) is immeasurable method and widely using for bonding of unique and precise systems – high quality metal-metal, metal-ceramic joints.

Gluing technologies have many disadvantages and for that have limited to use for ceramic to metal joints in UHV systems, these are higher outgassing rate, low thermal shock stability, lower mechanical stabilities, etc.

Mechanical sealing method for ceramic-metal joints in UHV conditions is not widely use for sealing difficulties and instabilities.

2.4. Experimental investigations

This section describes our ceramic to metal bonding experiments, particularly the processes of vacuum diffusion brazing, welding and gluing. We also present and discuss the designed and developed components for experimental studies of ceramic-metal joints.

2.4.1 Experiment – 1: active brazing of alumina to copper

Active brazing technologies are widely used in UHV technologies with an aim to braze ceramic to metals. The main advantage of this technology is the reduction of the necessary thermal cycles (only one brazing thermal cycle is needed). Active brazing technologies are reliable, durable, reproducible and cheaper than other metallization brazing technologies. We have investigated and carried out an active brazing of alumina (F99.7) and copper and the aim of this section is to present the details.

It is known that the wetting angle of ordinary solders for ceramic is very large (110-130^0), and sometimes is as large as 180^0 [82]. This fact makes the usage of ordinary solder for our purposes simply impossible.

Fortunately, special solders containing active Ti and Zr metals give us a possibility to braze ceramic to metal directly. The contact angle for this kind of solders can be as low as 10-20^0. The above mentioned brazing (in fact the entire chain of procedures; brazing, annealing, etc.) of alumina (F99.7) and copper has been performed in a vacuum furnace by making use of active Ti-Cu-Ag brazing.

Max. temperature	2000 ^{0}C
Vacuum level	10^{-6}Torr
Heater	Tungsten
Power	35KW
Working chamber size	150/150/460mm
Chamber cooling	Water
Chamber shielding	Molybdenum
Heater voltage increasing and decreasing	Manual

Table 2.4.1.-1: The main parameters of vacuum furnace.

The active components in such kinds of solders give possibility to create joints between ceramic to solder and solder to metals. There is, however, a delicate tradeoff between the possibility to braze a ceramic component to a metallic one and the mechanical properties of the obtained joints. Particularly, if the active component content in solder is lower than some particular level, then the solder wetting angle can still be unacceptably large. On the other hand, if the active component content is very high, then the joint hardness is undesirably high.

The main view of vacuum furnace is shown in Figure 2.4.1.-1, while its main technical parameters are summarized in Table 2.4.1.-1. For purpose of achieving a high vacuum level (up to 10^{-6}mbar) the furnace is accompanied with a diffusion vacuum pump combined with a cylindrical vacuum pump.

Figure. 2.4.1.-1: The vacuum furnace.

We have performed an experiment trying to identify the effective parameters for active brazing of alumina to Cu. Figure 2.4.1.-2 demonstrates the dependence of the furnace temperature on time. The brazing process consists of a warming-up phase, an isothermic conversion phase and a cooling-down phase. The cooling-down process was realized with a speed of approximately 7^0C/min in order to decrease the mechanical stresses in joints.

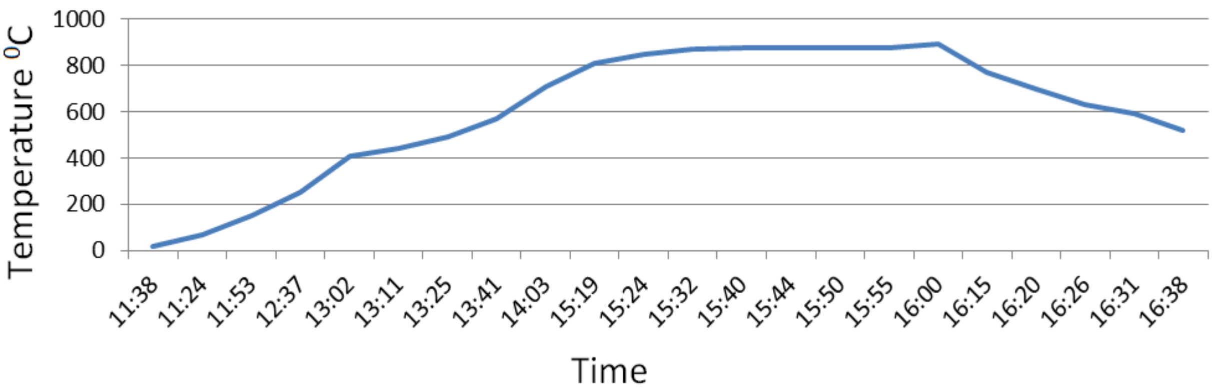


Figure.2.4.1.-2: Temperature dependence on time for brazing process.

The processed experimental samples are demonstrated in Figure 2.4.1.-3:

a) the ceramic-metal joint in the vacuum furnace,

b) the brazed joint,

c) the mechanically treated joint,

d) the ceramic-metal joint with a crack.

b.

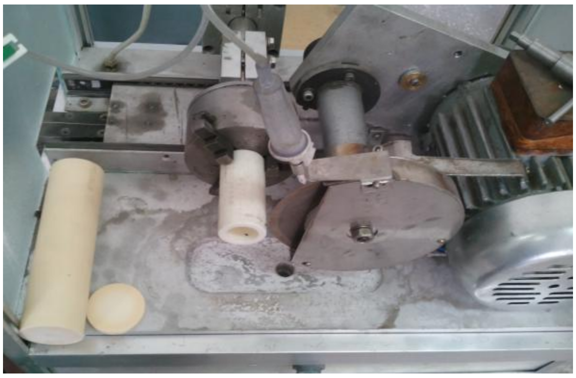
d.

a.

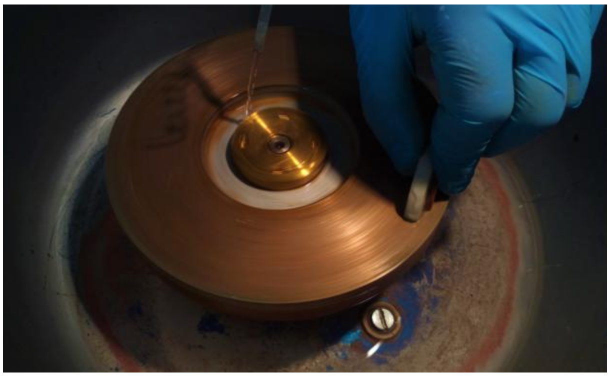
c.

Figure 2.4.1.-3: The treated samples.

The experiment was performed in a vacuum of 10^{-6} Torr and the temperature being around 820 ^{0}C. Two different temperature sensors have been used for controlling the brazing temperature for effectively warming up and cooling down.



a.



b.

Figure.2.4.1.-4: a. Diamond machining machine, b. diamond polishing disc.

After brazing process the cracks are shown in ceramic near brazed zone (Figure 2.4.1.-3 – d). Differences of thermal expansion coefficient of ceramic and metal or machining processes of joints can be reasons for cracks on ceramic. During cutting process of ceramic disc the temperature was strongly increases in contact of copper.

Increasing level - times	50x - 1600x
Eyepiece	WF 10x/20mm, WF 10x/20mm (With a scale), WF 16x/13mm
Planochromatic Objective lenses	5x/0,12 20x/0,35 40x/0,65 100x/1,25
Table size	180x165
Range of movement	50x40mm
Light filter	Blue, green, red, white
Digital camera	CMOS 9Мп
Transmitted permission	4096x3288
Software	Micam (Netherlands)

Table 2.4.1.-2: MMT-9C metallurgical microscope with parameters.

The surface of machined sample (Figure 2.4.1.-4-a) has been polished in diamond disc (Figure 2.4.1.-4-b). The parallelism and roughness of joint surface is very important for metallurgical analyzes. After these processes the jointed sample were polished in felt by chromium oxide (Cr_2O_3)-green component.

Figure 2.4.1.-5: Metallurgical microscope.

The final stage of joint preparation for metallurgical analyses is etching process. The etching process realized by aqua regia. Aqua regia is a mixture of nitric acid and hydrochloric acid (1:3 by volume).

All metallurgical analysis have been done by MMT-9C metallurgical microscope. The main technical parameters are shown in Table 2.4.1-2. and picture of MMT-9C metallurgical microscope are shown in Figure 2.4.1.-5. Main results from metallurgical analyses (metallurgical structure of ceramic-metal joint interaction) are shown in Figure 2.4.1.-6 [83].

The received layers between (Figure 2.4.1.-6-b) alumina ceramic (1) and Cu (8) are interlayer zone (2), interlayer with high Ti-Ag (Cu) content (3), interlayer zone (4), Ag content (5), Ag solder (6) and interlayer zone between Ag solder and Cu (7).

As shown in pictures the sub layers have small crystal size and as evaluation of this kind of structures are intermetallic structures with higher hardness.

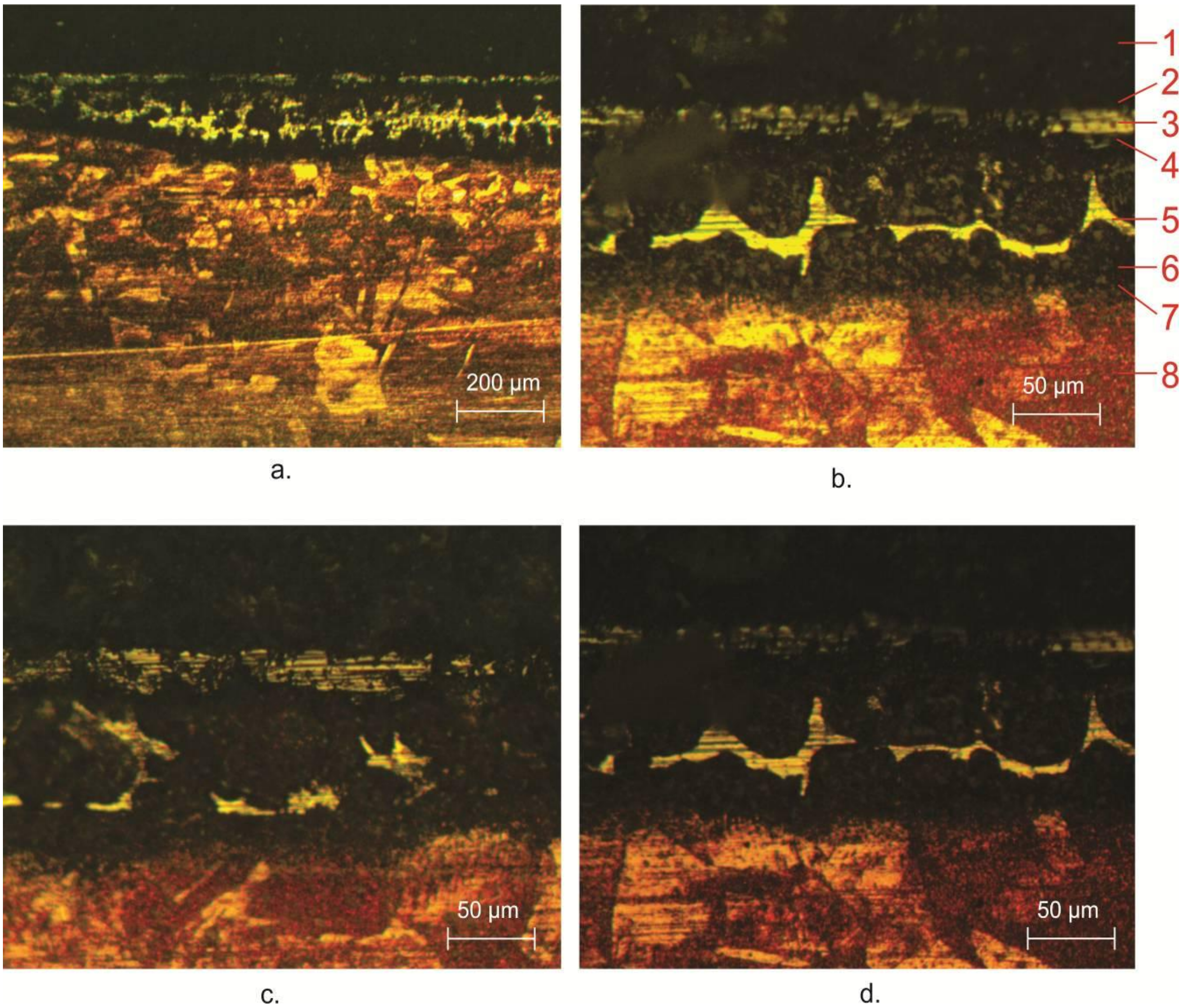


Figure 2.4.1.-6: The microstructure of alumina-copper joint.

The second layer (2) is TiO_2 and after that is mixture of TiO_2 with ceramic.

As mentioned Batygin et al., the Ti is captured O_2 from ceramic at 750^0C and higher temperatures, and some quantities of Al. Under some temperatures is created TiAl intermetallic structures. For understand the structures of brazing interlayer it is important to use phase diagrams. In literature mentioned binary and ternary phase diagrams. In case of many components alloys (higher 3) it is very difficult to evaluate the structure form joined materials sub layer.

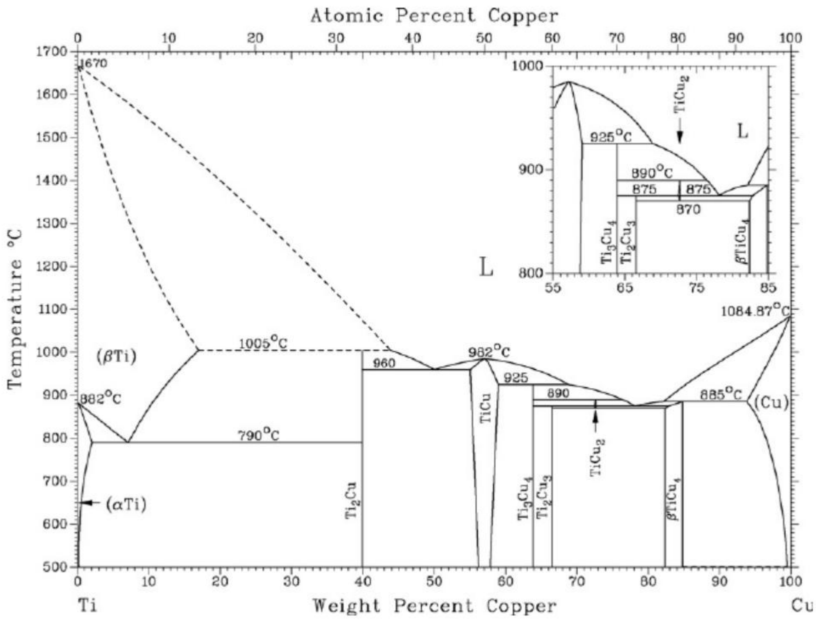


Figure 2.4.1.-7: Binary phase diagram of Ti-Cu.

The binary phase diagram for Ti-Cu is presented in Figure 2.4.1.-7. Especially the intermetallic structures are generated based on Ti-Cu mixtures. Actually Ti-Cu phase is eutectic. The phase diagrams are give possibility to evaluate of alloys properties (crystal structure, melting point, etc.) depends on components percentage in allow and temperature.

Evaluation and understand of phase diagrams are give possibility to reduce or avoid intermetallic structures from brazing zones.

Alloy	Ti/Cu	Microhardness kgf/mm^2
$TiCu_3$	0.8/3	380
TiCu	0.8/1	379: 195
Ti_2Cu_3	1:2	360: 314
Ti_2Cu	3:2	257

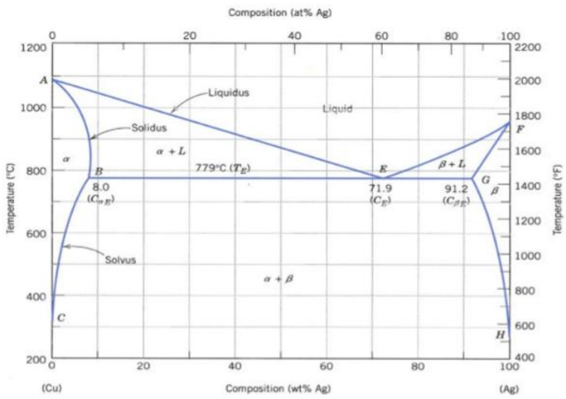
Table 2.4.1.-3: The micro-hardness level for Ti-Cu intermetalic structures.

Ti-Cu alloy have many different chemical compositions with different physical properties. Chemical formula and physical properties of Ti-Cu allow is depends on content percentages and temperatures.

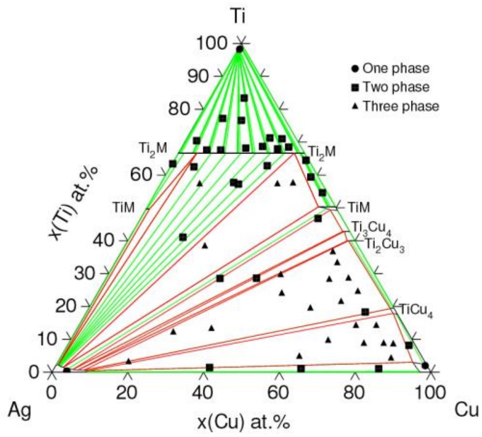
Micro-hardness of Ti-Cu mixtures are presented in Table 2.4.1-3 (Batygin, et al.[51]).

Ag72-Cu28 alloy are widely using in vacuum brazing processes as solder for UHV components. Ag72-Cu28 is reliable, effective and ideal solder in high wettability, brazability for many metals like Cu, Cu alloys, Ni, etc. the binary phase diagram for Ag72Cu28 are presented in Figure 2.4.1.-8 (a). The melting point of Ag72-Cu28 is 780 ^{0}C

Ti-Ag-Cu is very important for brazing processes, especially for brazing of ceramic materials. The ternary phase diagram of Ti-Ag-Cu are shown in Figure 2.4.1.-8 (b) [83 - 87].



a.



b.

Figure 2.4.1.-8: a- The binary phase diagram of Cu-Ag. b- The calculated and experimented phase diagram of Ag-Cu-Ti system at 700◦C

The ternary phase diagram of Ti-Ag-Cu (Figure 2.4.1-8-b) are shown that considering on temperature and component percentages in content can receive of three different phases.

If Ti content is higher in solder that hardness level is high, if Ti level is lower in solder than wettability of solder is lower. Depending on ceramic and metal type it is necessary to choose (theoreticaly and experimentaly) more effective level of solders (Ti, Cu and Ag).

2.4.2. Experiment – 2: vacuum brazing of ceramic to metals based on ceramic metallization technology

A more reliable and effective method for ceramic to metal brazing is the molybdenum-manganese technology. Molybdenum-manganese method gives a possibility to obtain quite high quality vacuum tight ceramic-metal joints.

During these experiments are brazed alumina to copper, alumina to stainless steel, etc.

As alumina are used F99.7 and 95% alumina. The first step is was materials preparation – mechanical machining (based on the design), cleaning.

The metallization process diagram for 95 % alumina (temperature dependence on time) is presented in Figure 2.4.2.-1. [88].The metallization process are realized in 10^{-6} Torr high vacuum and in 1600 ^{0}C high temperature conditions.

For metallization processes is very important warming up and cooling down velocities. Considering the differences of thermal expansion coefficients of ceramic and metals the warming up and cooling down processes must be as much as possible low – especially cooling down process for reducing mechanical stress in interlayer zone of ceramic-metal joint.

The cooling down process has been realized very slowly 3-7 ^{0}C/min.

Each type of ceramic materials has effective metallization content. Depends on requirements for ceramic-metal joint the metallization content can be different.

For metallization processes is very important of metallization powder content (components percentages) and preparation technologies.

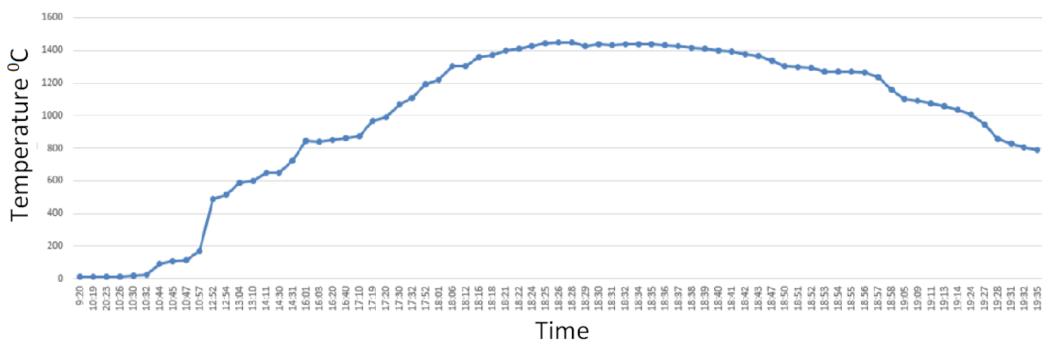


Figure 2.4.2.-1.: Regime of Metallization.

For alumina ceramic materials are widely using metallization mixtures based on Mo and Mn – molybdenum-manganese technology. Molybdenum-manganese technology is effective and reliable for alumina ceramic materials.

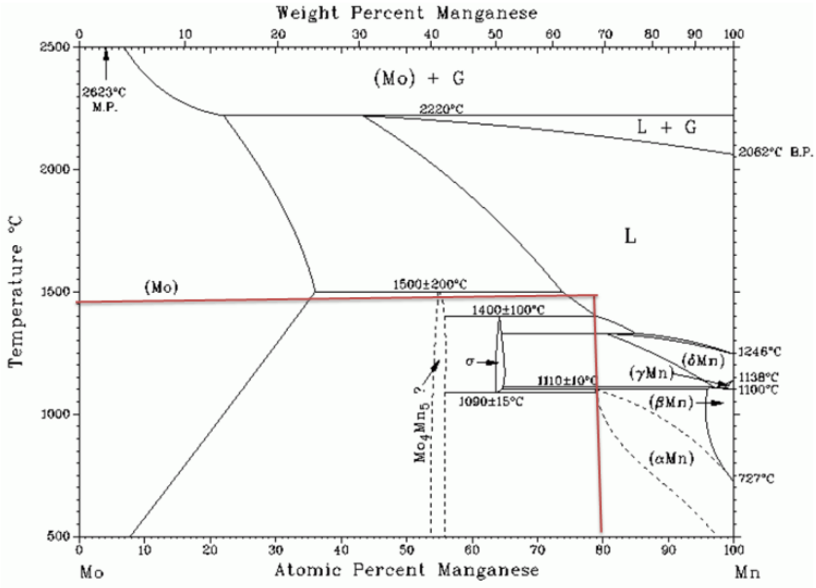
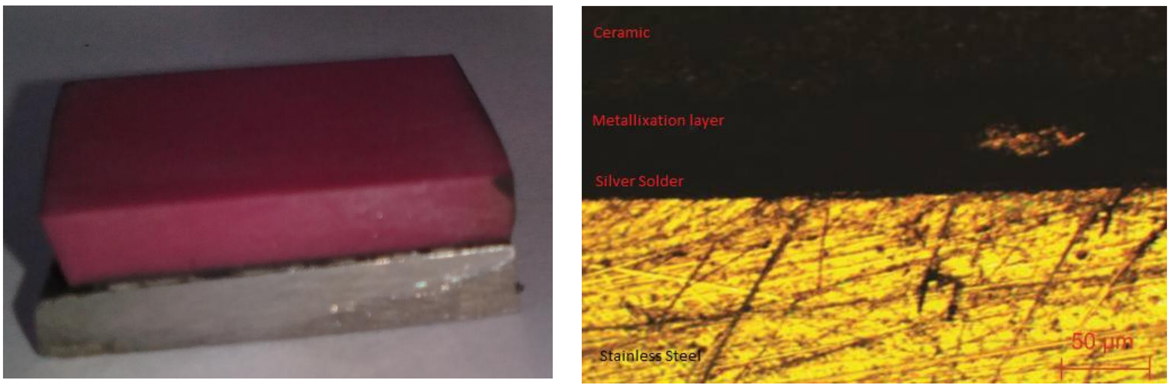


Figure 2.4.2.-2.: Phase diagram of Mo-Mn.

The phase diagram of Mo-Mn are presented in Figure 2.4.2.-2.

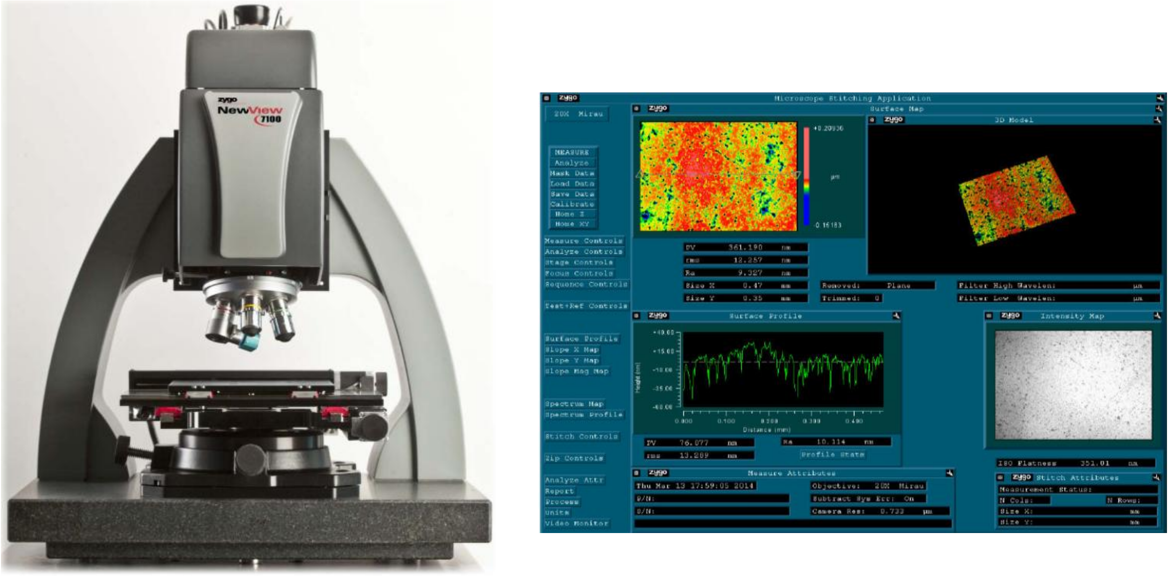
The Mo/Mn 80/20 mixture has been used for metallization of ceramic.

Metallization contents are received based on experimental and theoretical experiments.



a. b.

Figure 2.4.2.-3.: 95% alumina to stainless-steel joint.



a. b.

Figure 2.4.2.-4.: a. Interferometric profilometer. b. Porosity and roughness level of ceramic samples.

After metallization process is follow of Ni plating. Ni plating process has been realized based on electro-chemical galvanic method.

Metallized and Ni plated 95% alumina to stainless steel have been brazed in vacuum furnaces under high temperature conditions. The ceramic-metals brazed joint (a) and metallurgical investigated zone (b) are presented in Figure 2.4.2.-3 .

Before metallization process the ceramic sample are cleaned and investigated in interferometric profilometer. The roughness of experimented ceramic is 0.2µm (Figure 2.4.2-4-b).

The main view of interferometric profilometer are presented in Figure 2.4.2-4-a. The interferometric profilometer give possibility to understand the porosity level and roughness level of ceramic.

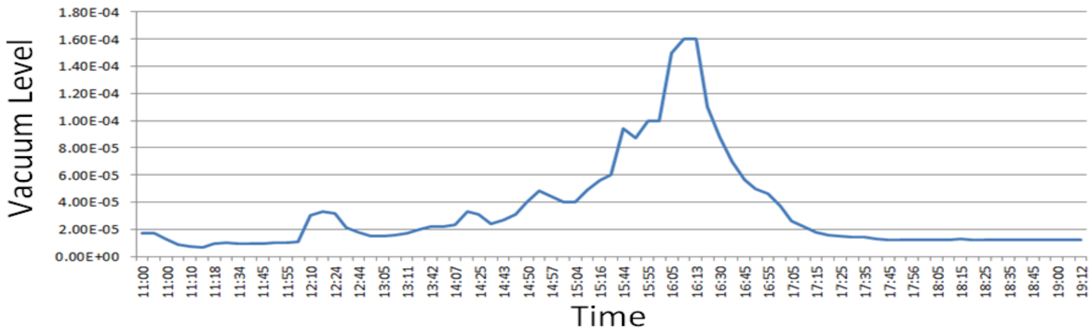
Corresponding roughness and porosity values of materials are very important for high quality ceramic-metal joints.

The second part of experiment-2 based on ceramic metallization technologies are dedicated of alumina F99.7 to copper brazing technologies.

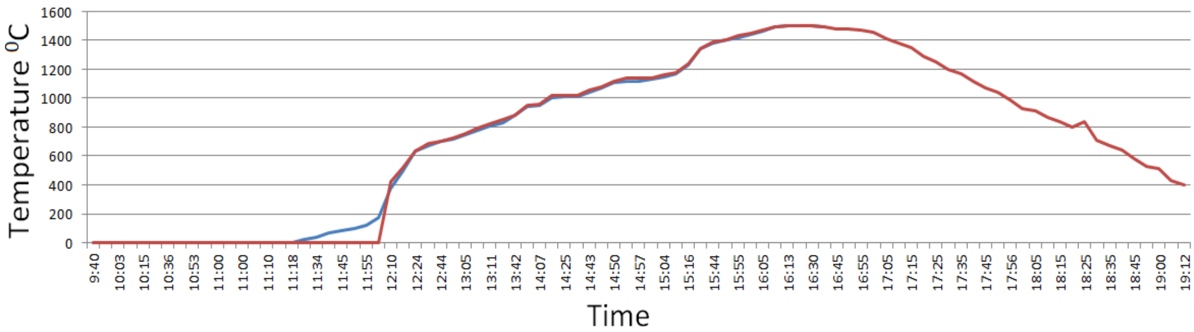
The materials for metallization mixtures must be vacuum compatible (low outgassing rate, low vapor pressure, etc.).

Metallization of ceramic materials – Molybdenum/manganese metallization.

Corresponding ceramic samples (alumina), metallization process and mixture of powder (Mo, Mn, etc.) are prepared (mechanically machined, cleaned, etc.).



a.



b.

Figure 2.4.2-5.: a. - Time dependence on vacuum variations. b. Time dependence on temperature.

The metal powder mixture has been spreaded in to ceramic surface. With samples the chamber was pumped down in rare vacuum pumps after that is switched on of diffusion pump.

Under high temperatures the materials is outgassed. The lower outgassing level is important for high quality joints during brazing process. The dependence of ougassing on vacuum is presented in Figure 2.4.2.-5-a. The brazing process is presented in Figure 2.4.2.-5-b (Time dependence on temperature).

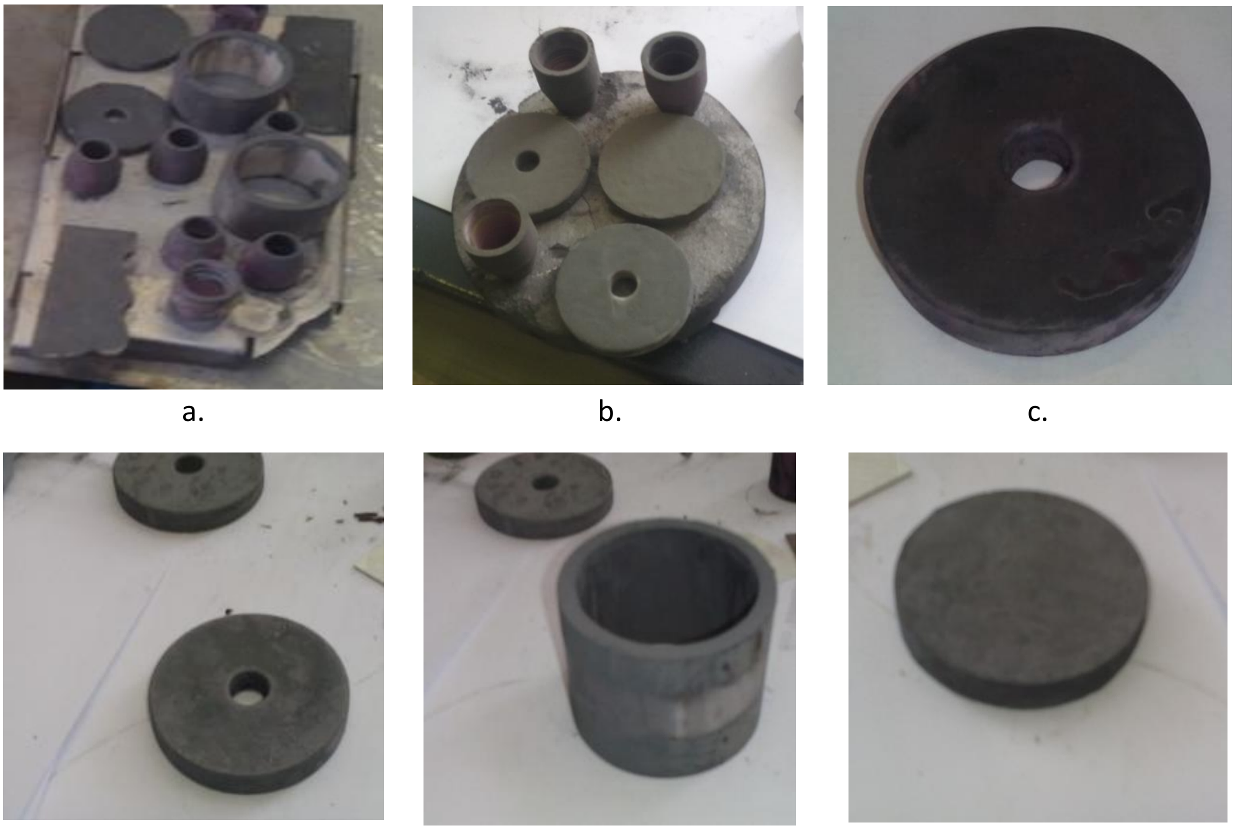
Special hot filament and thermocouple vacuum gauges are used for measuring vacuum in vacuum furnaces.

The maximum outgassing value of materials depends on materials purity level and temperature.

All materials and systems before moving to vacuum chamber must be carefully cleaned for moving detergents, oil and other impurities.

Warming up and cooling down process dependence on time for ceramic metallization process in vacuum environment is presented in Figure 2.4.2.-5-b.

Two special tungsten-rhenium thermocouples are used for temperature measuring under high temperature conditions.



a. b. c.

d. e. f.

Figure 2.4.2.-6: Metallized ceramic samples.

Before metallization procedure it is very important to evaluate the ceramics surface quality.

Real metallized ceramics are presented in Figure 2.4.2.-6.

Nickel Plating based on Galvanic method.

The metallized ceramic samples have beem Ni plated based on electro-mechanical method. Special electrolits are used. Real Ni plated ceramics are presented in Figure 2.4.2.-7.

Figure 2.4.2.-7: Ni plated ceramics.

The thickness of Ni for received ceramics items is app. 5µm.

Ni layer is for avoiding of intermetailic zone between Cu to Mn-Mo system. Ni plated ceramic items have been temperature preparated in vacuum condition under slowly warming up and cooling down processes.

Silver Soldering. The ceramic to metal items have been brazed using special silver solder under vacuum and high temperature conditions. Different solders have been used. One of effective solder is Ag72-Cu28.

The brazing experimental results from ceramic to metal items (vacuum dependence on time (a) for high vacuum, vacuum dependence on time (b) for rough vacuum and temperature dependence on time (c) for brazing process) are presented in Figure 2.4.2.-8.

During vacuum brazing process are used piece of solder for fixation of melting point of solder. As mentioned silver solder don’t has wettability to ceramic and under melting point of solder it become ball.

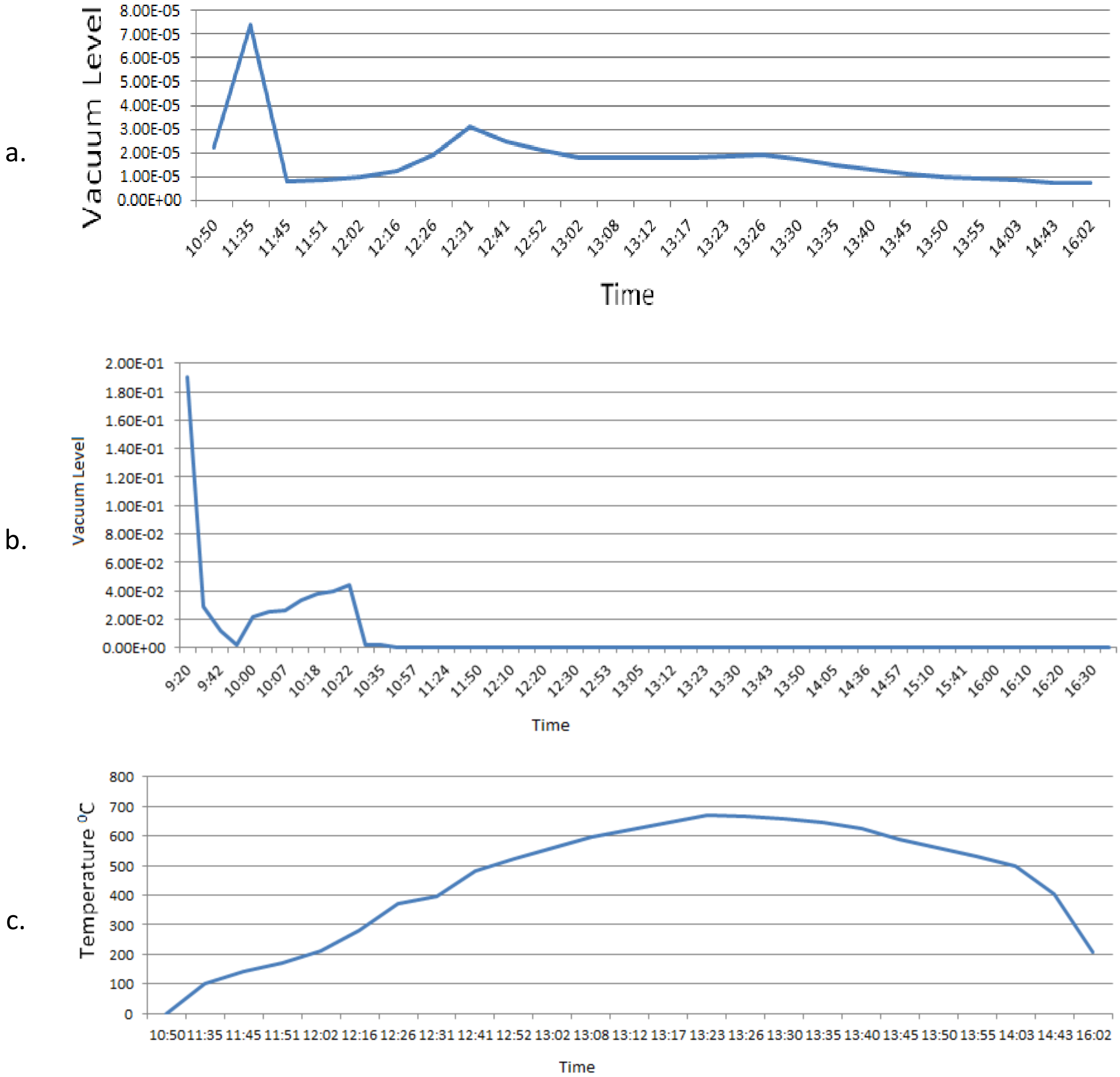


Figure 2.4.2.-8.: Brazing process (Ag soldering).

The warming up and cooling down processes have been realized by electrical current value regulation in the resistance heater.

a. b. c.

Figure 2.4.2.-9.: Ceramic-metal brazed joints.

The brazed alumina (F99.7) to Cu items based on molybdenum-manganese technologies are presented in Figure 2.4.2.-9.

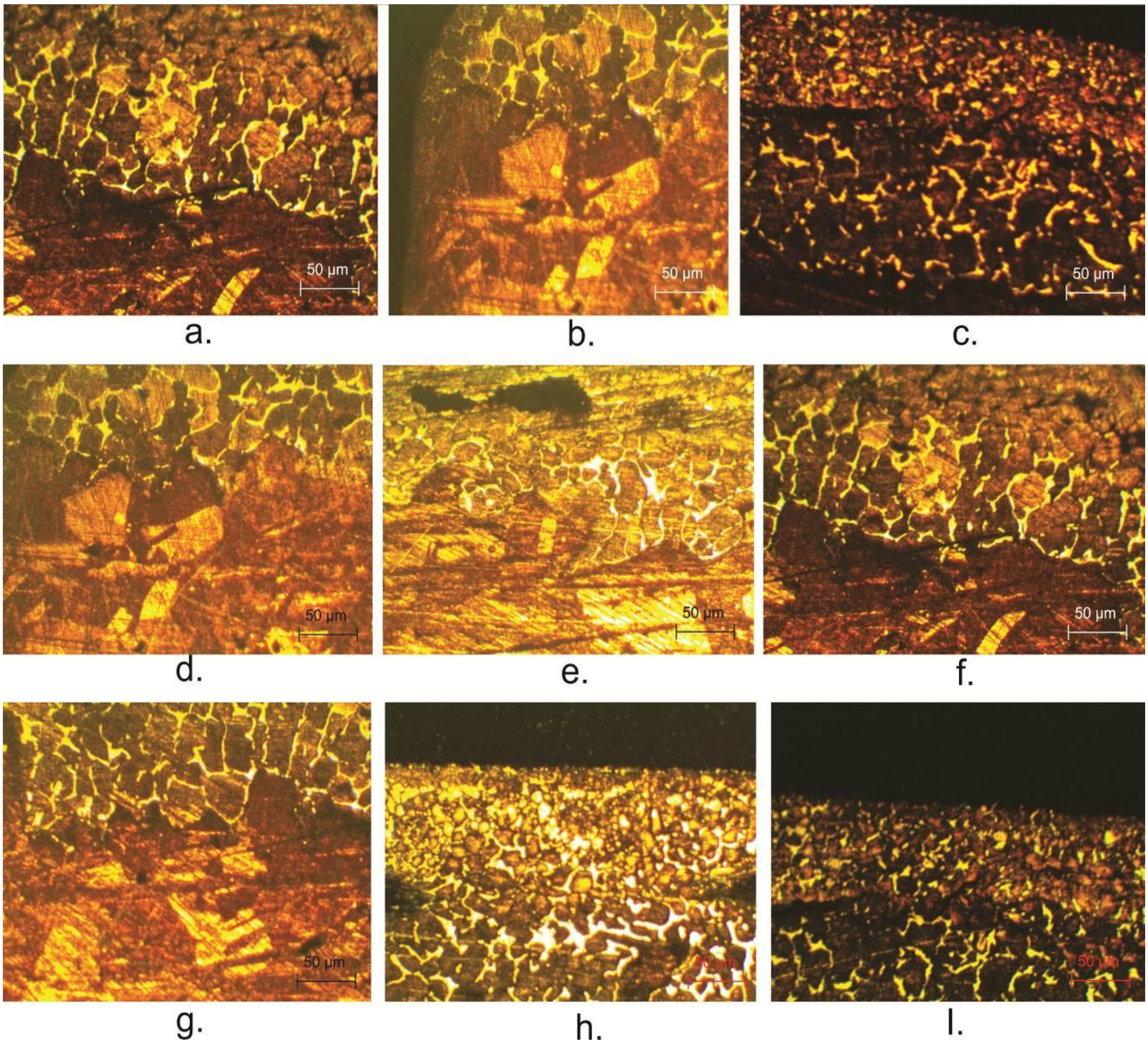


Figure 2.4.2.-10: The microstructures of brazed ceramic-metal joints.

The F99.7 alumina to copper brazed joints have been machined for metallurgical microscopy investigations. The metallurgical microscopy investigations have been realized for brazed ceramic-metal joints. The metallurgical investigation results (microstructure) of brazed joints are presented in Figure 2.4.2.-10. The brazed joints contain of emptiness in the interlayer of items according to metallurgical (microscopy) investigations.

The importance of pressure equally effects and corresponding pressure level on items during brazing process are mentioned as conclusions according to realized experimental results for high quality vacuum-tight ceramic-metal joints.

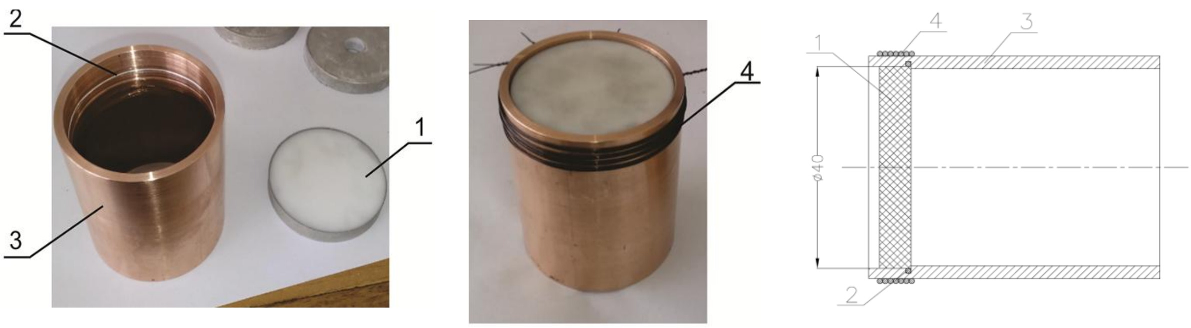
2.4.3 Experiment – 3. Vacuum brazing of ceramic to metals based on different materials fixation methods.

The effective fixation technique for ceramic to metal joints during brazing process is important to receive of high quality vacuum-tight ceramic-metal joints.

This experimental section is dedicated to the description of experiments on different fixation technologies used during vacuum brazing procedures.

Molybdenum-magnanese and active brazing technologies are used for these experiments. The ceramic (F99.7), copper, stainless steel, solder and other materials are prepared. In case of molybdenum-manganese technologies the ceramics has been metalized under high temperature conditions. After that it has been Ni-plated by an electro-chemical method.

The final brazing procedure was the vacuum brazing of ceramic to metals based on Ag solder under high vacuum and high temperature conditions.



a. b. c.

Figure 2.4.3.-1: The view of the ceramic to metal sample and the assembling scheme.

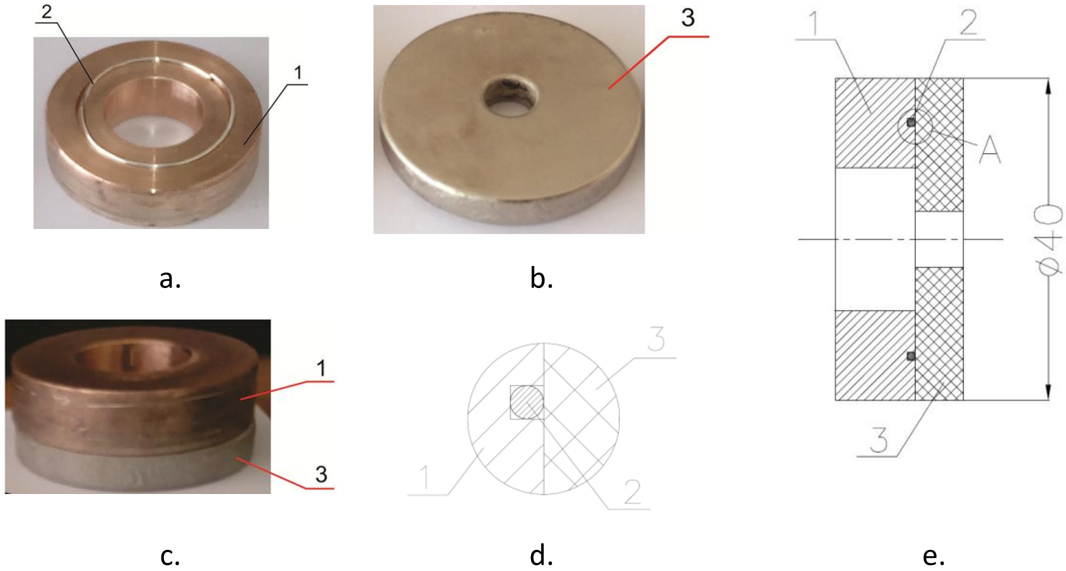


Figure 2.4.3.-2: The view and assembled scheme of sample 2.

Different fixation methods have been used for these experiments. The preparation of the samples consisted of a mechanical treatment of the samples, preparation of the solder, fixation of all items and components moving to the vacuum furnace. The F99.7 type of alumina has been selected as ceramic materials. Some ceramic components have been used with metallized layers (Mn-Mo+Ni), and other ceramic samples have been used without metallization layers.

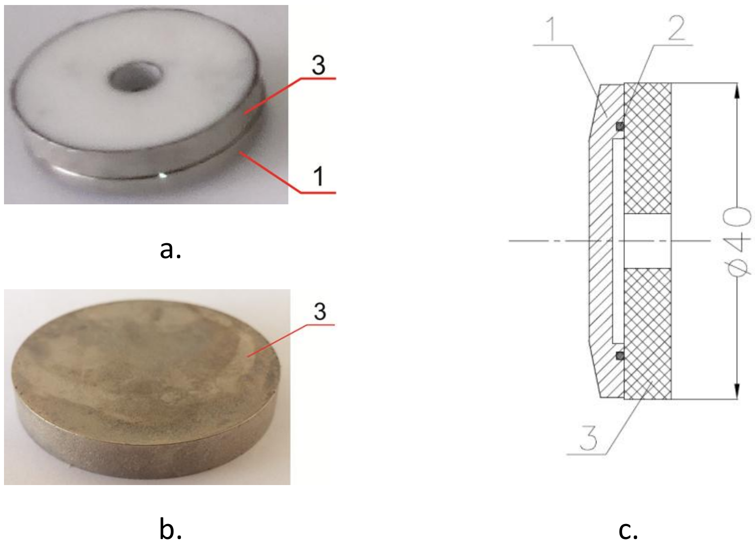


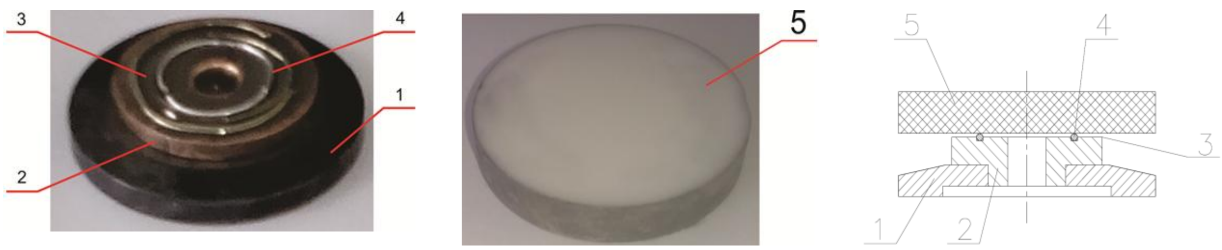
Figure 2.4.3.-3: The view and section of assembled sample 3.

The sample 1 is shown in Figure 2.4.3-1, where one can see a copper pipe (3), which has a corresponding place for fixation of the corresponding Ag72-Cu28 solder (2) (see Figure 2.4.3-1.a.). Additionally, alumina ceramic F99.7, which has a metallization layer (Mn-Mo+Ni), is also fixed.

The assembled and fixed sample is shown in Figure 2.4.3-1-b. The section view of the assembled sample (with Mo wire fixation) is shown in Figure 2.4.3-1-c. After assembling such a sample, a 1mm molybdenum wire (4) is screwed into the ceramic cylinder and fixed there (Figure 2.4.3-1.a,b,c).

The view of sample 2 is shown in Figure 2.4.3.-2. The sample 2 also has a copper pipe (1) (see Figure 2.4.3-2.-a), which has a grove for fixation of Ag72-Cu28 solder (2). The metallized F99.7 (3) alumina (Mn-Mo+Ni) has been used (Figure 2.4.3-2-b). The section-cut of the assembled sample is shown in Figure 2.4.3-2 (d,e). The brazed joint (Cu to alumina) is presented in Figure 2.4.3-2-c.

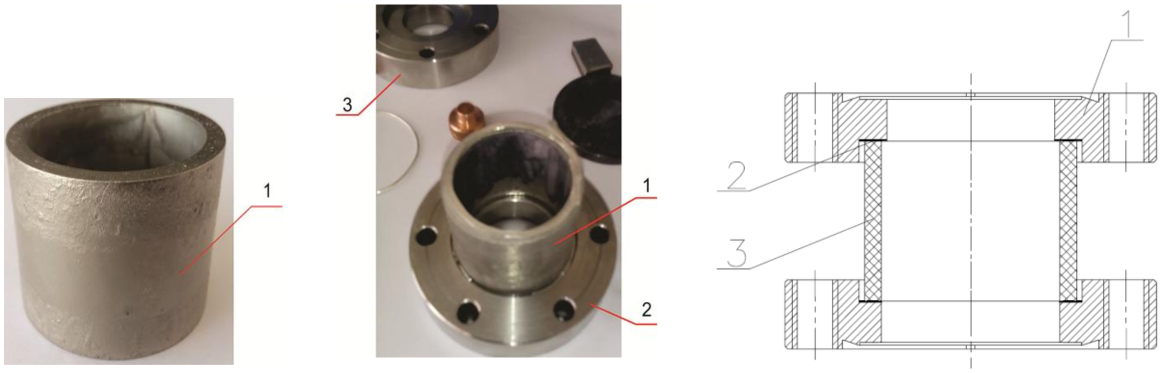
The overall view of the sample 3 is shown in Figure 2.4.3.-3. The sample 3 is consists of stainless steel flange of type 304SS (1), in which we have brazed a ceramic cylindrical sample (3). The stainless steel (c) has a grove for fixation of Ag72-Cu28 solder (2). An metallized alumina (3) plate (b) is fixed on this (a). Sample 3 is for experiments of a molybdenum-magnanese brazing method.



a. b. c.

Figure 2.4.3.-4: The overall view and section view of sample 4.

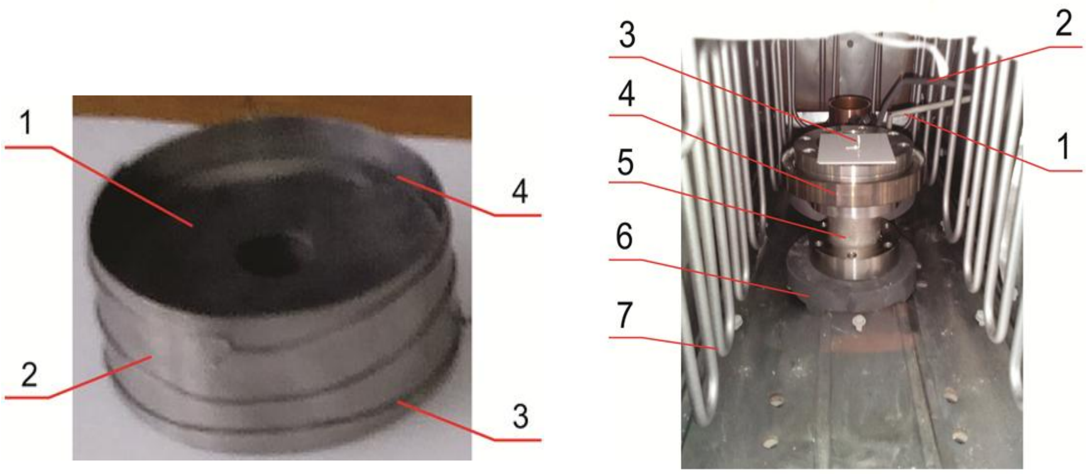
The sample 4 is shown in Figure 2.4.3.-4. The main components of the assembled sample (Figure 2.4.3.-4-a) is a stainless steel (1), Cu item (2), Ti-Ag-Cu solder (3), Ag solder (4) and ceramic (5) - Figure 2.4.3.-4-b. The section view of assembled sample is shown in Figure 2.4.3.-4-c. Sample 4 is for experiments of an active brazing technologies.



a. b. c.

Figure 2.4.3.-5: The realistic view and the drawing of the sample 5.

The sample 5 is presented in Figure 2.4.3.-5. This one is a metalized ceramic pipe (1), in the edges of which we have fixed a stainless steel flanges (2) – Figure 2.4.3.-5-(a,b). The section view of assembled systems is presented in Figure 2.4.3.-5-c (1-stainless steel flange, 2-solder, 3-ceramic pipe).



a. b.

Figure 2.4.3.-6: The view of the sample 6 and inner part of the vacuum chamber.

The sample 6 is presented in Figure 2.4.3.-6-a. This sample is a ceramic disc (1) without metallization, in the edges of which we have fixed a kovar foils (2) using Mo wire fixation (3). In the contact zone of the ceramic and kovar we have put a mixture of silver solder and Ti powder (4).

After preparing the samples we have moved them into the vacuum furnace as shown in Figure 2.4.3-6 (b). The samples (5) under mass (4) are placed between the corresponding ceramic component (6) and the heater (7), used solder (3) for fix of solder melthing point.

The temperature measurements are realized using a sensitive thermopair (1 and 2). Precise temperature measurements are very important for vacuum brazing procedures. After placing the samples into the vacuum furnace one closes the door of the vacuum chamber and pumping down up to very high level vacuum.

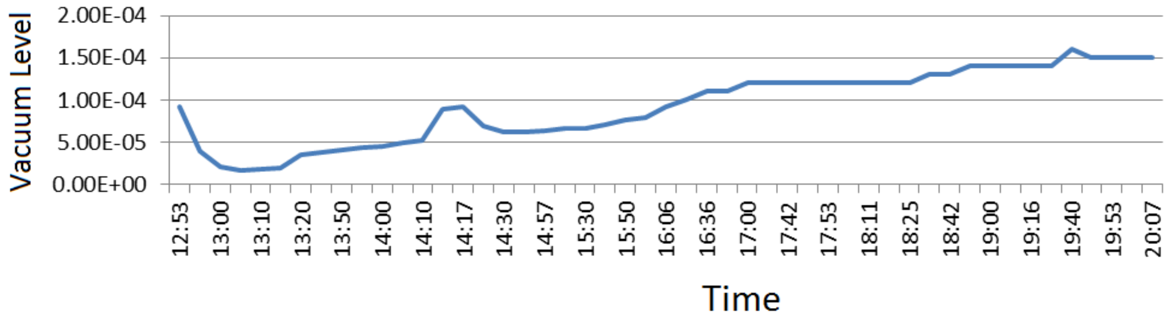


Figure 2.4.3.-7: Vacuum brazing regimes.

The implemented brazing process (Vacuum level dependence on time) under high temperature condition is presented in Figure 2.4.3.-7.

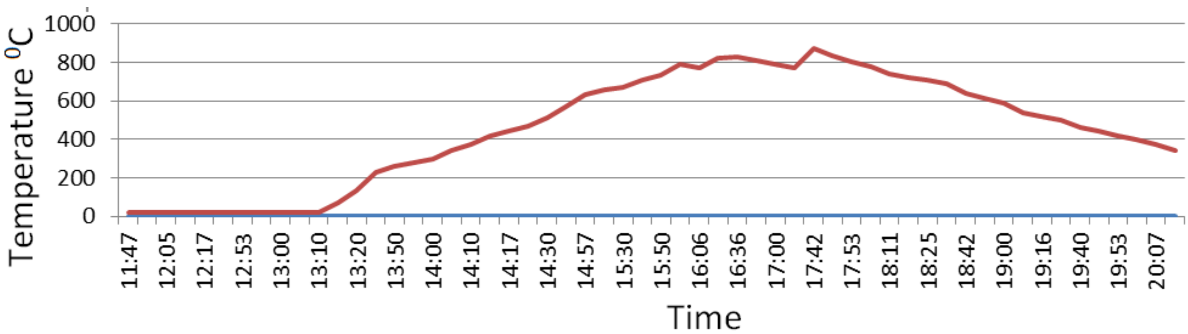
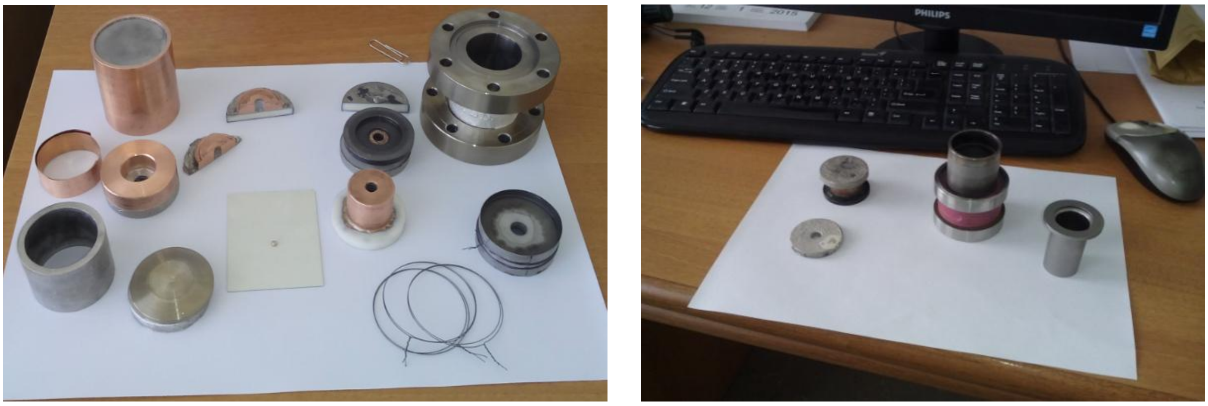


Figure 2.4.3.-8: Vacuum brazing regime.

The implemented brazed process of ceramic to metal items (temperature dependence on time) is presented in Figure 2.4.3.-8.

The view of brazed ceramic to metal items (experiment 2) are presented in Figure 2.4.3.-9 (a.- 99.5% alumina ceramic to metal joints, b.- 95% alumina ceramic to metal joints).



a. b.

Figure 2.4.3.-9: The main experimental results (brazed joints) from experiment 2.

The brazed joint of kovar to alumina is presented in Figure 2.4.3.-10-a. The brazed joint of Cu to alumina used Mo wire fixation method under brazing high temperature conditions is presented in Figure 2.4.3.-10-b. The brazed joint of metalized alumina to stainless steel is presented in Figure 2.4.3.-10-c.

a. b. c.

Figure 2.4.3.-10: Brazed samples from experiment 2.

The effective fixation importance of ceramic to metals are mentioned for high quality vacuum-tight ceramic metal joints under brazing high temperature conditions according implemented experiments.

The implemented brazing process for ceramic to metal joints under brazing high temperature conditions are presented in Figure 2.4.3.-11 (temperature dependence on time) and in Figure 2.4.3.-12 (vacuum level dependence on time).

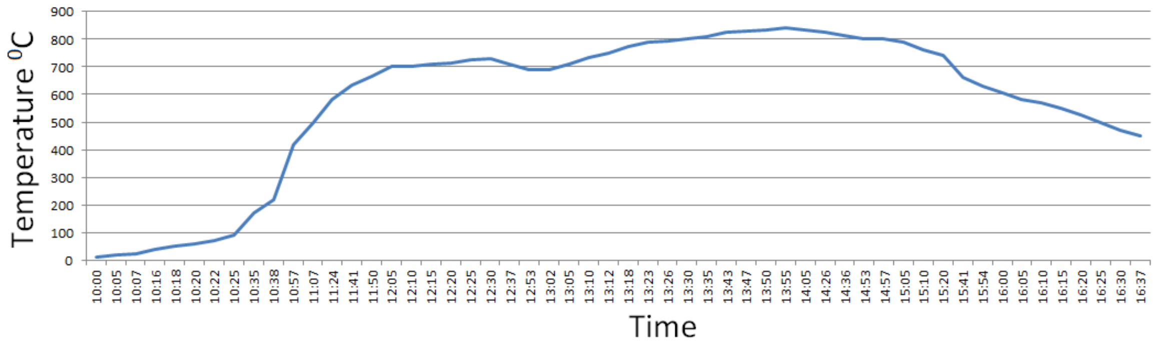


Figure 2.4.3-11: Temperature dependence on time for brazing process.

The ceramic-metal brazing regimes have been received by experimentally.

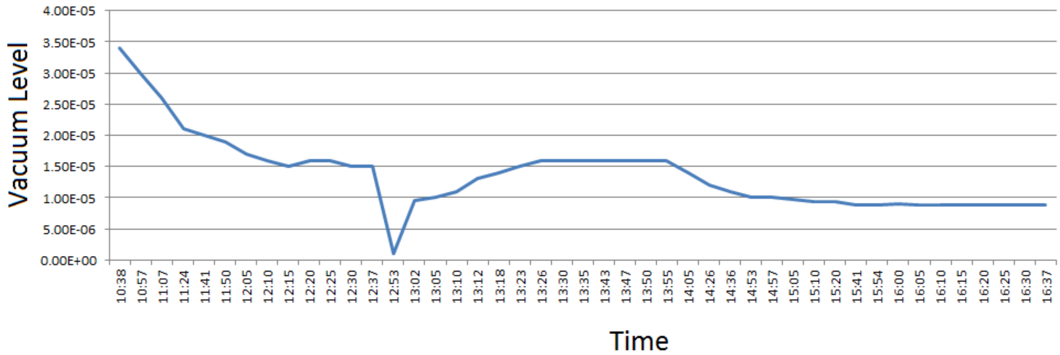


Figure 2.4.3.-12: Vacuum level dependence on time for brazing process.

2.4.4. Thermo-compression bonding techniques

Thermo-compression bonding techniques are widely used for ceramic-metal bonding. At CANDLE Synchrotron research Institute we haves designed and fabricated the first diffusion welding machine in Armenia [89, 91]. Its realistic view is presented in Figure 2.4.4. The maximum temperature was 1500 ^{0}C which was achieved using an induction heater. The maximum vacuum level was 10^{-5} Torr which was achieved using a turbo pumping station. The maximum pressure of 1Atm was achieved based on pneumatic cylinder.

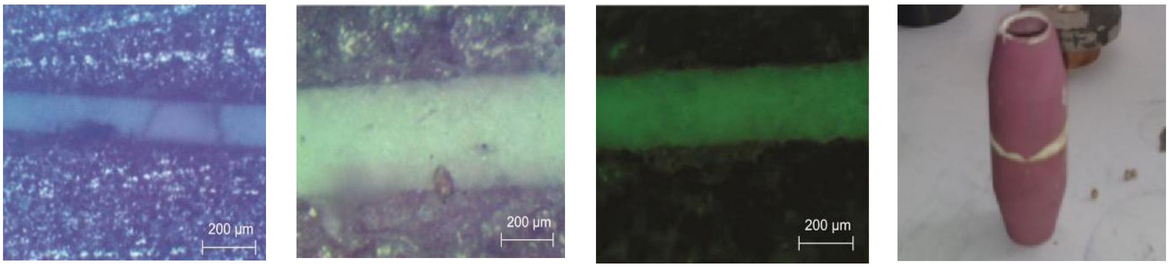
The mentioned diffusion welding machine is a very flexible and reliable experimental station and it gives a possibility to implement different kinds of experiments for bonding metallic components to metallic components and metallic components to ceramic ones.

We have managed to obtain copper to copper and copper to stainless steel joints based on this diffusion welding machine.

Figure 2.4.4: Diffusion welding machine.

2.4.5. Experiment – 4: gluing and mechanical sealing techniques

Gluing techniques are yet another method for joining different types of materials, for example, metal, plastic, ceramics, etc. Using adhesive silicate it was possible to glue alumina to Cu, alumina to stainless steel and alumina to alumina.



a. b. c. d.

Fig. 2.4.5.1: Ceramic-metal and ceramic-ceramic joints based on gluing.

The Figure 2.4.5.1 depicts the microstructures of glued alumina to stainless steel (a), alumina to alumina (b) and alumina to Cu (c). The real view of glued ceramic to ceramic is presented in Figure 2.4.5.1.-d. The special silicate gluies have been used for experiments.

Such a metal-ceramic bonding has both advantages and disadvantages. One of the main disadvantages of this technique is the low mechanical strength of the joint, its low working temperature and the short lifetime. On the other hand, it is very easy and fast to realize such a bond.

We should also mention that sometimes it is enough to mechanically seal the two components. Such a method is used in accelerators, but UHV systems typically do not widely contain such components (ceramic-metal systems).

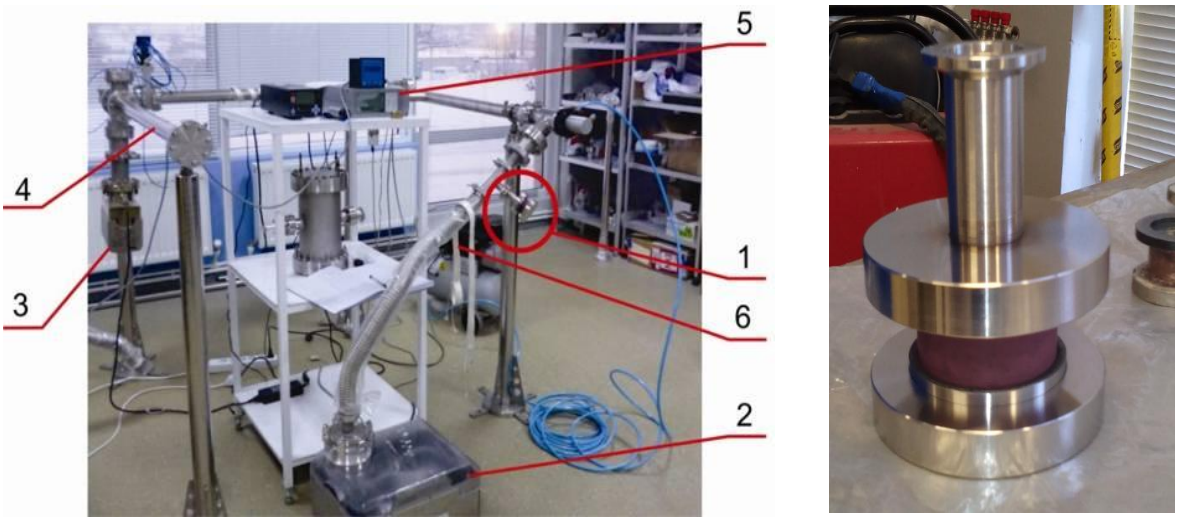
2.5. Ceramic-metal simulations and experiments

The cylindrical vacuum-tight ceramic-metal joint has been simulated using a software based on **F**inite **E**lements **A**nalysis (FEA) method. Additionally we have performed a set of experiments on our UHV test stand in order to find the effective bake-out temperature for such joints [92].

The left panel of Figure 2.5.1-a shows the setup on the test stand. The numbers correspond to:

1. the ceramic-metal joint on the UHV test stand.
2. the TPS pump,
3. the ion pump,
4. the vacuum chamber
5. the vacuum measuring gauges.

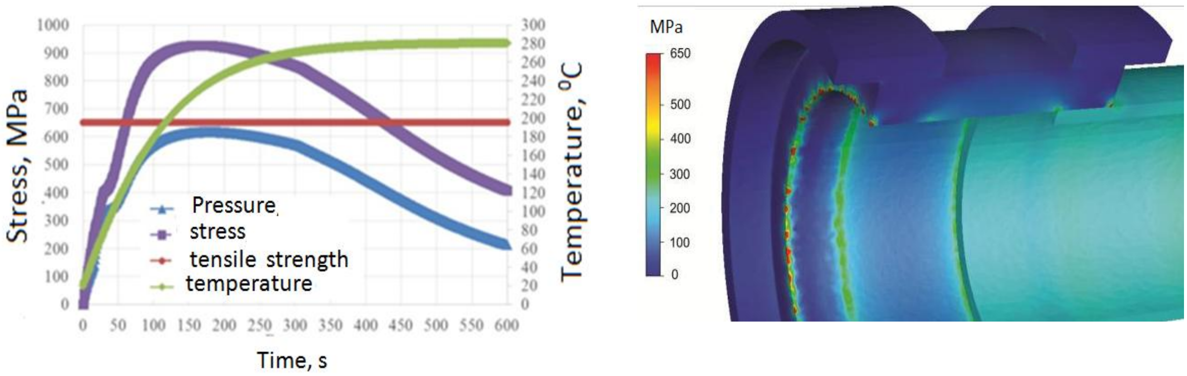
Our tested sample is shown in Figure 2.5.1-b. We have performed our tests in UHV with a temperature of about 130 ^{0}C.



a. b.

Figure 2.5.1.: Vacuum test stand (a) and the brazed ceramic-metal joint (b).

Our simulation results, on the other hand, are presented in Figure 2.5.2. The left panel of this figure shows the pressure, stress, tensile strength and the temperature as functions of time (see Figure 2.5.2-a). The stress values of the vacuum-tight ceramic-metal joint being subjected to a bake-out temperature is shown in Figure 2.5.2-b. As a result we have obtained the maximally acceptable operation temperature for vacuum-tight ceramic-metal joints to be 134 ^{0}C. This is confirmed with the experiments as well.



a. b.

Figure 2.5.2.: The dependence of mechanical properties of the ceramic-metal joint on time.

2.6. The summary of the Chapter 2

- First of all, we have performed a thorough literature review for materials and brazing technologies for vacuum-tight ceramic-metal joints. We have found that molybdenum-manganese metallization technology is an acceptably reliable technology for fabrication of vacuum-tight ceramic-metal joints.
- We have performed brazing experiments (active brazing and Mn-Mo+Ni technologies) as well as several calculations to understand the effect of external pressure on the quality of the metal-ceramic joints.

Chapter 3: New diffusion brazing methods and thermo-mechanical simulations for ceramic-metal joints

There are many different techniques which are used to braze ceramics to metals. The quality of materials' fixation and the effect of pressure on the relevant surfaces of the items are very important for the process of brazing.

The methods of material fixation and the techniques of pressure creation depend on types of material (for example, the physical-mechanical properties) as well as the procedure of brazing (i.e. the heating and cooling specifications). The main purpose of materials' fixation and pressure creation during the brazing procedure is to provide hermetic contact of materials (i.e. a larger contact area) without distortion, emptiness and with a high mechanical and thermal stability under the high temperature conditions.

The main purpose of this chapter is to present a new method of diffusion brazing developed by us, which is applicable for brazing ceramic to metal and is performed under high brazing temperature conditions in order to increase the joint's quality. Below we present the main ideas, purposes and the working principles as well as the main description of this new brazing method.

3.1. A proposal of a new diffusion brazing method applicable for systems containing dissimilar components with complex geometric shapes

As we have already mentioned above the fixation of materials and the pressure creation on materials during brazing processes are very important and they determine the quality of the joined materials. Here we present the new brazing new technique developed by us applied for brazing ceramic components to metallic ones in the case when the components have complex geometric shapes [93].

This invention is dedicated to the technique of brazing by pressure and heating effects related to that. Particularly, its main aim here is the diffusion brazing of conically shaped ceramic components to metallic ones and it can be applied in many areas, such as accelerator technology, electronics, RF systems.

In general, the diffusion welding or diffusion brazing method under vacuum and mechanical pressure effect, as well as under high temperature conditions is one of the most popular diffusion bonding technologies (Kazakov N. F., Materials diffusion welding, machine-building, 1976, P.312) [94]. It has been invented by Kazakov and is realized in a vacuum chamber under 10^{-5} Pa vacuum and very high temperature conditions of 0.8-0.9 T_m, where T_m is the lowest melting point of the materials, as well as under mechanical pressure of P = 10-15 Mpa, using an isothermal conversion of 20 – 40 minutes of duration. Induction heaters can be used for locally heating up the items in the contact zone.

The method has several advantages and disadvantages. Particularly, only this welding method makes it possible to braze some types of materials given some special requirements at a very high quality level. At the same time this is a very challenging procedure.

The pressure mechanism fixes the items mechanically and has a limited usage for the complex geometric shapes. Also, the pressure mechanism can not equally spread the force on the items' surfaces. Another drawback of diffusion welding method is the possibility of damaging the subtle surfaces and structures of the items.

The new diffusion brazing method, which is being discussed here, gives a possibility to braze dissimilar items with complex geometric shapes. It gives possibility to increase the quality of the joints, i.e. the vacuum tightness, mechanical strength, stability of the surfaces and the structure of the brazed items.

The main idea of the new brazing method is the pressure creation on corresponding surfaces of the items being brazed, which is based on pressure difference between the inner and outer volumes of the contacted items. The inner pressure must be lower than the outer pressure of the contacted items. The brazing method gives a possibility to create equally distributed pressure on the outer surface of the items. The exerted pressure level on items depends on the type of materials, their structure, geometric shape, brazing temperature, surface roughness and several other specifications.

The warming-up process up to the corresponding temperature and the isothermal conversion of items is the next stage of the brazing procedure after the pressure creation.

The realization of the invention: In order to explain the main operational principle of our method below we describe a real example.

The schematic view of our new brazing method is presented in the Figure 3.1.1. The conically shaped ceramic component (1) and the metallic flange (4) were selected as an example for a demonstration. We have metallized the conically shaped ceramic component before brazing. One can use various materials and techniques (e.g. metallization, cleaning etc.) for a desirable quality of vacuum-tight joints. The chamber (12) contains a gas input port (10), a gas output port (11), which is used for pumping down, secondary gas output (9) port (again used for pumping down), a support holder (8), a support (6), a heater (7). The material of the chamber is inert and it gives possibility to keep high cleanness level in the chamber during the brazing process.

The metallic flange (4) and the conical ceramic component (1) divide the volume of the chamber into an outer volume (a) and inner volume (b) (see Figure 3.1.1.). A carefully designed compensator (5) separates the metallic flange from the support item (6). Ceramics or metal can be used as materials for the compensator depending on the brazing conditions (pressure level, temperature, used materials, geometric shape, etc.). Ceramic materials are preferable as compensator materials due to their lower thermal conductivity.

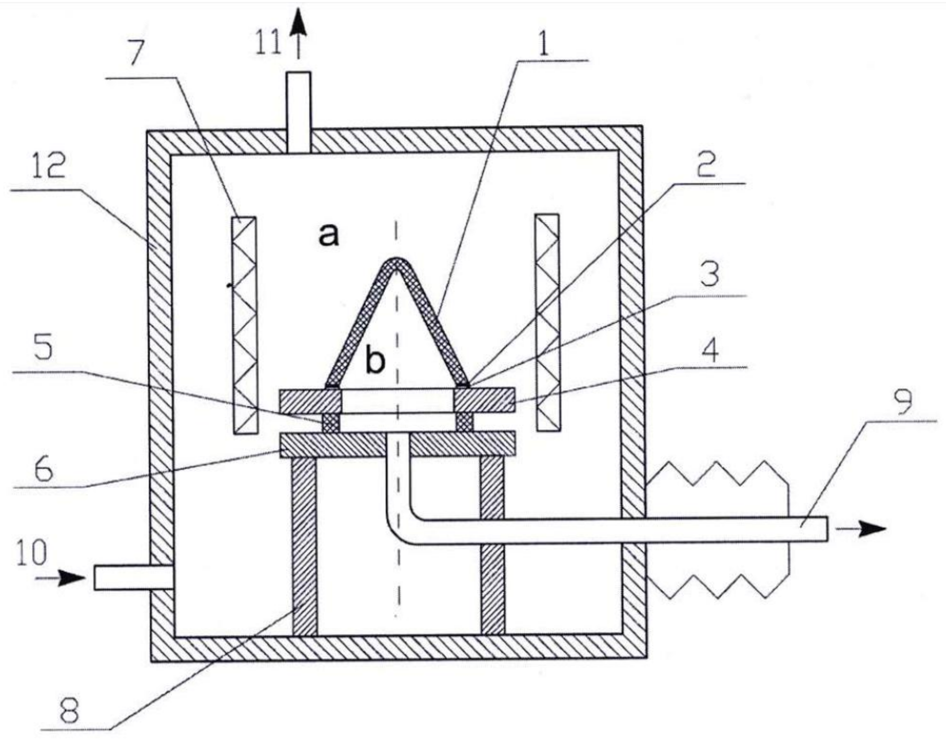


Figure 3.1.1: The schematic view of the new brazing method.

Special solder foil (3) is used in interlayer of conical ceramic and metal flange. Solder type depends on the joint requirements.

The first step of invention realization is carefully assembling and moving the ceramic-metal system to the chamber.

The second step is simultaneously chamber pumping down (vacuum) from the ports (11 , 9).

The port (11) closes in case of corresponding vacuum level in chamber, the heater switches on and the port opens (10). The input port (10) supplies inert gas to the chamber.

Supporting gas pressure and flow rate is regulated by special mechanism.

An equal pressure is created in the case of pressure differences between inner (b) and outer (a) volumes of ceramic-metal joint.

The equal pressure gives a possibility to a precise and hermetic fixation of ceramic-metal joint due to the pressure differences.

The pressure values on ceramic surface is regulated based on the inner (b) and outer (a) values of ceramic-metal joint pressure differences. According to the corresponding gas input port (10) and pumping down port (9) – both ports can be flexible to regulate gas pressure levels and flow rates.

The outer (a) pressure value is regulated by N_2, Ar inert gases which can be input into the chamber. The Inert pure gases give possibility to avoid from the oxidation and impurities of items during the brazing processes. The fixation of ceramic to metal flange (pressure differences) is followed by a warming up process of items up to corresponding high temperature and isotherm conservation.

The isotherm conservation duration depends on the material type, solder type, brazing temperature level and geometric shape which can take 1-10 min.

The solder foil is plastically deformed under the corresponding brazing temperature and pressure (the force effect depends on the pressure difference). As a result of solder plastic deformation it is chemically reacted with metal and ceramic simultaneously. Reaction intensity of ceramic-solder and solder-metal determines the further joint quality.

Induction heaters can be used for local heating of items for metal component. It will be more effective for vacuum-tight ceramic-metal joints to use resistant heaters which can give possibility to warm up and cool down the joint equally with desirable velocity.

High temperature (brazing temperature), isotherm conservation, pressure value (pressure differences) and other brazing parameters depend on materials geometric shape, materials type (ceramic, metal, solder, metallization, etc.), structures, vacuum tightness level, mechanical strength, surface properties of items (surface roughness, surface stresses, oxidation level, cleaning level, etc.).

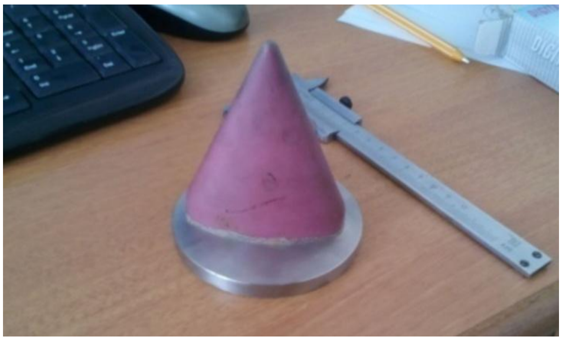
According to the brazing new method there is a possibility to receive and regulate pressure on the items precisely in a wide range. The method provides a bigger contact area of brazing materials.

Brazing new method can be used for vacuum brazing for similar and dissimilar metal-metal, metal-ceramic precise joints.

3.2 Experiments on the new diffusion brazing method

We have performed a set of experiments studying the pressure difference mechanism. Particularly, we have been able to achieve bonding between two components, one being a conicaly shaped ceramic (22XC) and the other being a stainless steel flange.

b.



a.

c.

Figure 3.2.1: The experimental machine (a) and ceramic-metal joint (b,c).

The experimental chamber (a) and the obtained ceramic-metal joints (b, c) are presented in the Figure 3.2.1.

We have used a cold, epoxy-based welding glue in order to bond the ceramic component to the metallic one in a low vacuum condition. The glue has been put between the conical ceramic and the flange's interlayer section. After moving this ceramic-metal system into the chamber, we have proceeded to the second step, by pumping down to a vacuum level of up to 10^{-3} Torr from lower pumping port. The ceramic-metal system separated the chamber into the inner and outer volumes. During the pumping down process the pressure in the inner volume was lower than the pressure in the outer volume. The maximum pressure difference between the inner and the outer volumes was about 1 Atm. As a result there was a pressure effect on the outer surface of the ceramic component because of the pressure difference. The ceramic equally pressed the glue to the flange under the pressure difference and we received a joint zone with a larger contact area and without bubble formation.

This experiment was just a preliminary step for testing the proposed pressure effect mechanism on complex-shaped items and as a result we have obtained desirable results. The next step will be to perform an experiment of a new brazing method under the high temperature and high vacuum conditions, or in an environment filled with an inert gas.

3.3. A new method of diffusion bonding for ceramic and metal materials with cylindrical shape

We have additionally extended the diffusion bonding method to the items with cylindrical components made of ceramic and metal [95]. We have demonstrated that the new diffusion bonding method can be effectively used in accelerator technologies, electronics and other areas where one needs to design and fabricate cylindrical ceramic-metal joints.

There are some diffusion brazing and welding technologies with advantages and disadvantages.

Whole (total) heating, lower regulation of temperature and pressure (force) of brazed joining systems are disadvantages for some diffusion brazing and welding technologies.

The diffusion bonding new method increases the temperature and the pressure regulation during the brazing process.

Local heating of bonding system is valuable advantage for the diffusion bonding new method which can be effectively used for precisely bonding small parts by local heating of difficult big systems.

The main advantages of new bonding method are the flexible regulation of temperature and the pressure with local heating possibilities of bonding items which increases the brazing quality of the precise and difficult cylindrical items.

The diffusion bonding new method gives a precise fixation possibility to the bonding cylindrical items.

The main purpose of the new diffusion bonding method is to increase the quality of joints, its high mechanical strength and vacuum tightness.

The realization of the invention: The main working principle (schematic view) and operational scheme of the new diffusion bonding method are presented in the Figure. 3.3.1.

The ceramic cylindrical item (1) is fixed to the inner side (inner surface) of a metallic item (2). The main purpose is to achieve a high quality bonding between the ceramic (1) and metal (2). The fixation of the materials must be realized as precise as possible. The precision of the fixation defines the quality of the joint. The materials fixing accuracy depends on the mechanical design and fabrication technologies (tolerance, roughness, etc.).

The diffusion bonding new method can be used for diffusion welding (without solders) and diffusion brazing (with solders) processes. The materials bonding with or without solders depends on the joint requirements (material type, mechanical strength, vacuum tightness, etc.). In a diffusion brazing case the solder is fixed in the ceramic (1) to metal (2) interlayer zone. Depending on the joint system the ceramic can have metallization layer before brazing process. The diffusion bonding new method can effectively be used for active brazing technologies depending on the joint specifications (material type, etc.).

According to the schematic view metal to ceramic system is fixed by Mo wire (4) using insulator layers (3). The isolation layer (3) can be specially fabricated ceramic pieces. The material for isolation layer must have high electrical resistance and high thermal conductivity. The special fixing (5) screws (6) are used to fix Mo wire to the insulator material.

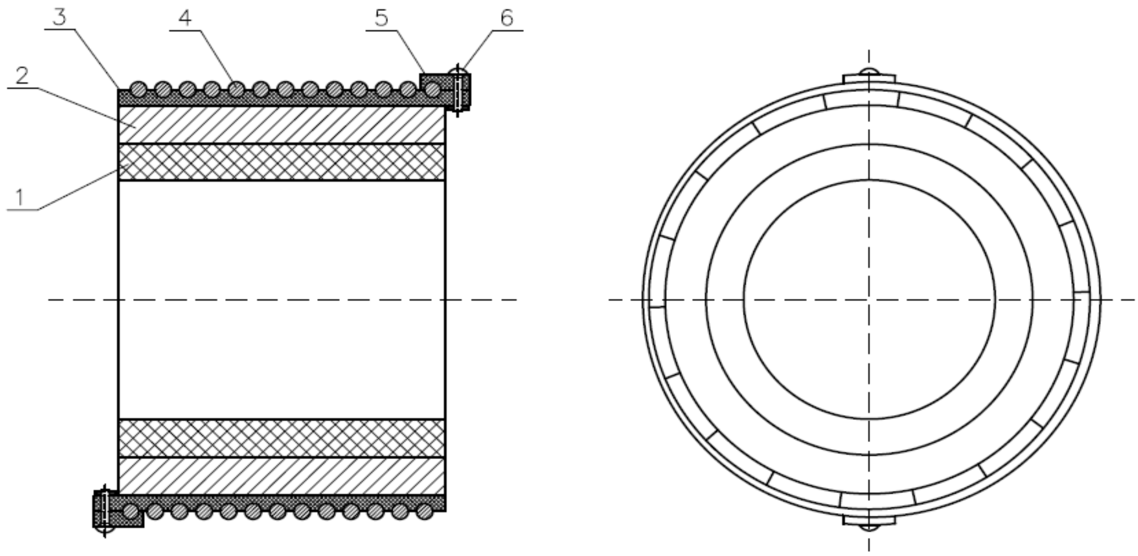


Figure 3.3.1.: The schematic view of the diffusion bonding new method for cylindrical items.

One of the main specifications of the diffusion bonding new method is the difference of thermal expansion coefficient of materials.

The ceramic item (1) must have a low coefficient of thermal expansion. The metal item (2) must have higher coefficient of thermal expansion than Mo wire.

The precise assemble is moved into the chamber (into a vacuum or inert gas environment). The warming up process of joints system is realized increasing the electrical current in Mo wire. The temperature can be regulated by the electrical current value of the Mo wire. The electrical insulation layer (3) is very important for the brazing process (avoiding dangerous electrical effect and short circuit) and it electrically insulates the Mo wire from the metal (2).

The ceramic can be used as an electrical insulator. As insulator beryllia (Beryllium oxide - BeO) is one of the effective ceramics. BeO has high thermal conductivity (330W/m K) and low electrical conductivity. The disadvantage of BeO is the poison property.

The items are warmed up according to the electrical current regulation in the Mo wire in vacuum or in inert gas environment.

The diameter, length, thread distances of Mo wire depend on the supplying electrical current level. The vacuum level or inert gas types (N_2, Ar, Kr, etc.) in bonding chamber depend on the brazing technology design and the joint requirements.

The temperature and pressure effects can be flexibly changed by the regulation of electrical current of Mo wire from power supplier.

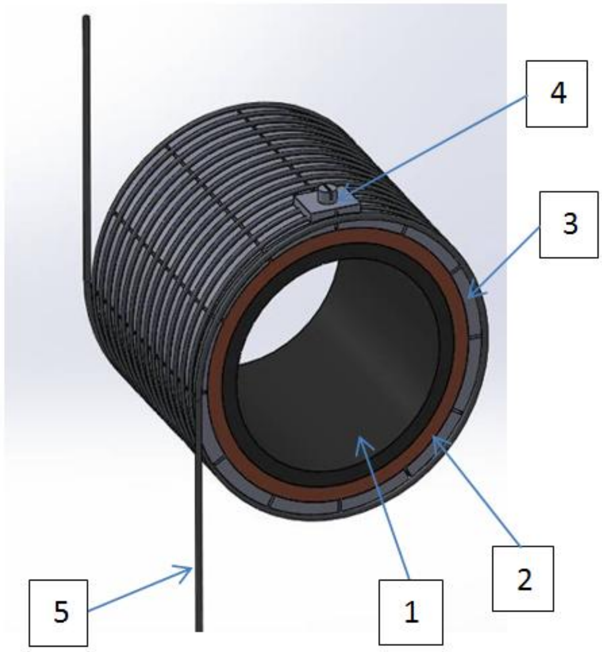


Figure 3.3.2: The 3D schematic view of the brazing new method.

The diffusion bonding new method can effectively be used for bonding the cylindrical ceramic to metal and metal to metals as high quality vacuum-tight joints.

Different preparation technologies for materials can be used before the main brazing process depending on the joint requirements and design (technical machining, temperature treatment, metallization, coatings, cleaning,).

The isotherm conservation is required during the bonding process under the high temperature and pressure effects conditions.

The isotherm conservation can be varied depending on the design (material type, surface properties, geometric shape, desirable physical-mechanical properties, etc.). Generally the isotherm conservation is varied from 10 to 60 min according to the joint specifications.

The 3D schematic view of the new diffusion bonding technology is presented in the Figure 3.3.2. The main components are ceramic (1), copper (2), insulation layer plates (3), molybdenum wire fixation (4) and molybdenum wire (5).

The main advantages of the new diffusion brazing method is the local heating, the flexible control of generated pressure and the temperature, the equal pressure effects on the materials. These advantages increase joints quality (high mechanical strength, high vacuum tightness, etc.).

3.4. The diffusion bonding process based on the molybdenum foil

For brazing processing of high quality joints it is a real challenge to generate, equally to spread and flexibly regulate the pressure values on the corresponding materials surfaces.

The method has been designed (based on the foil) to increase the received pressure equal value. Depending on the material type and bonding processes different kinds of foil can be used to receive pressure.

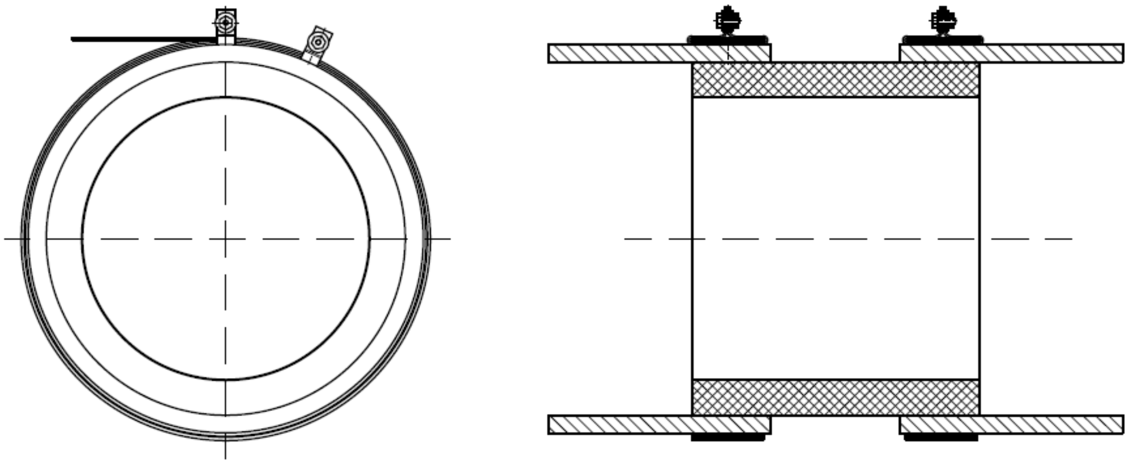


Figure 3.4.1.: The diffusion bonding scheme using the molybdenum (Mo) foil.

The foil must have as low coefficient of thermal expansion as possible.

The Mo has ideal thermo-mechanical properties for materials fixation in diffusion brazing processes. The Mo has low thermal expansion coefficient and high mechanical strength under the high temperature conditions.

The Mo foil pressure receiving mechanism is shown in the Figure 3.4.1.

This pressure receiving method can be effectively used for diffusion bonding procedures of cylindrical material.

The main advantages of this method are the equal pressure effects on the materials. The method gives a possibility to increase the quality of brazed joints (vacuum tightness, mechanical strength, etc.).

The tightness and layers quantity of Mo foil depends on brazing materials types (ceramic and metal), materials diameters, brazing technologies.

The local section view of ceramic-metal joint is presented in the Figure 3.4.2.

The joint consists of a ceramic (1), a metal (4), a Mo foil (3) and fixation parts for fixation using Mo foil (2).

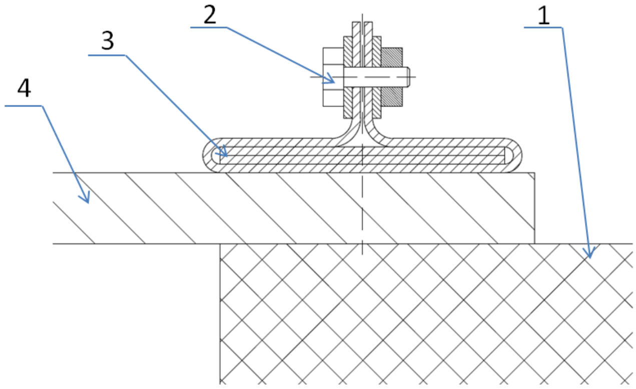


Figure 3.4.2: The diffusion bonding method using Mo foil.

The materials fixation method can be used for diffusion brazing of dissimilar cylindrical metal to ceramic and metal to metal joints for the accelerators UHV systems (vacuum breaks, vacuum windows, etc.). The method decreases the deformations of materials under the high temperature conditions comparing with wire fixation method.

The method can use the combination of Mo wire and foil.

3.5. The thermo-mechanical simulation of ceramic-metal joints in vacuum systems

The mechanical and thermal simulations are important to evaluate the operational and brazing properties of ceramic-metal joints.

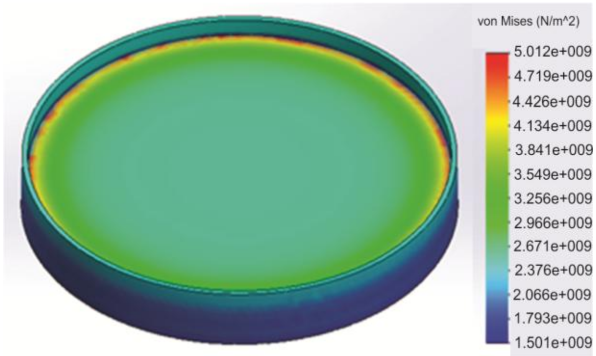
Many different developed methods are used for materials thermo-mechanical simulations. The thermo-mechanical simulations are important before fabrication, brazing and operation of ceramic-metal joints. Each simulation method (software) has corresponding accuracy level.

The simulations are preliminary evaluating methods for joint materials. The simulations results can be varied near the realistic results.

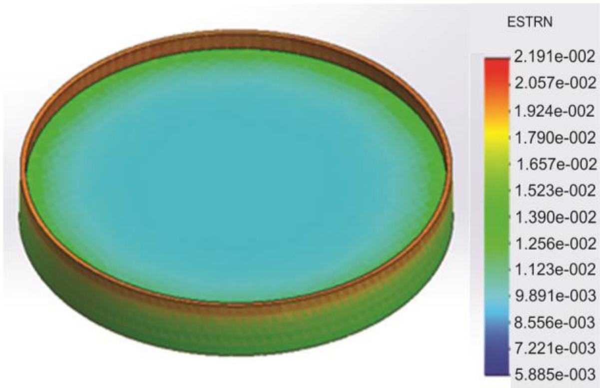
The thermo-mechanical simulation has been done using various combinations of ceramic-metal under the high temperature conditions. The thermo-mechanical simulations are carried out without taking into account the chemical reactions of materials under the high temperature conditions. The results of the thermo-mechanical simulations for ceramic-metal combinations are presented below. The FEA (finite element analysis) method is used for the thermo-mechanical simulation.

3.5.1. The thermo-mechanical simulation of the ceramic disc to Cu ring system

The thermo-mechanical simulation of ceramic to copper materials under the high temperature condition is presented in this section. The simulations have been done in static regime.



a.



b.

Figure 3.5.1.1.: The main results of ceramic-metal simulation under 850 ^{0}C.

The materials warming up, cooling down and isotherm conservation processes are not taken into consideration during simulations.

The 99.5% alumina has been selected for the simulation. The Cu ring with 1mm tightness is used for simulations.

The results of the thermo-mechanical simulation of ceramic disc (diameter – 70mm) to Cu ring under 850^{0}C temperature without any fixation mechanism are presented in the Figure 3.5.1.1 (stress (a), strain (b) and displacement (c)). The joint has low stress and strain value under 850^{0}C temperature conditions. The maximum stress value is 5.01e+0.009N/m^2. The copper ring has highest strain value and the maximum strain value is 0.0219.

Taking into consideration the simulation results the fixation importance of ceramic to Cu joint has been mentioned.

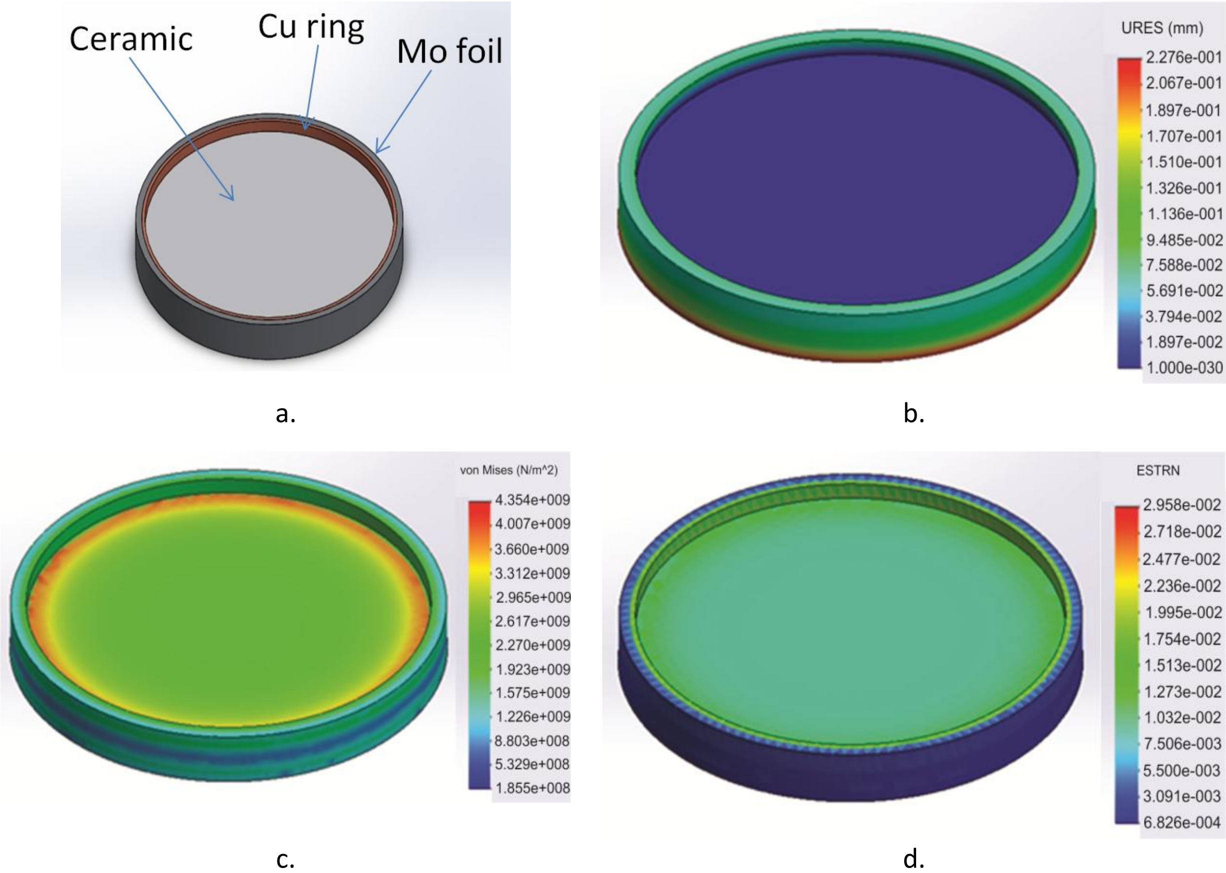


Figure 3.5.1.2.: The main results of ceramic-metal simulation under 850^0C through Mo foil fixation system.

The thermo-mechanical simulation has been implemented for ceramic disc to Cu ring under 850^0C temperature conditions through Mo foil fixation method. The assembling scheme of ceramic disc to Cu ring using Mo foil is presented in the Figure 3.5.1.2-a. The simulation results (displacement (b), stress (c) and strain (d)) are presented in the Figure 3.5.1.2.

The contact zone of ceramic disc to Cu has high stress under 850^0C temperature conditions according to the simulation results (Figure 3.5.1.2-c). The maximum stress value is 4.35E+0.09 N/m^2.

The solder and chemical processes are not taken into account during the simulations.

The Cu has high displacement (Figure 3.5.1.2-b). The maximum displacement value for copper is 0.22mm under 850^{0}C temperature conditions. The maximum strain value for joint is 0.0295 (Figure 3.5.1.2-d).

According to thermo-mechanical simulation results the Mo foil fixation can be used for brazing the cylindrical ceramic to metal items under the high temperature for high quality joints.

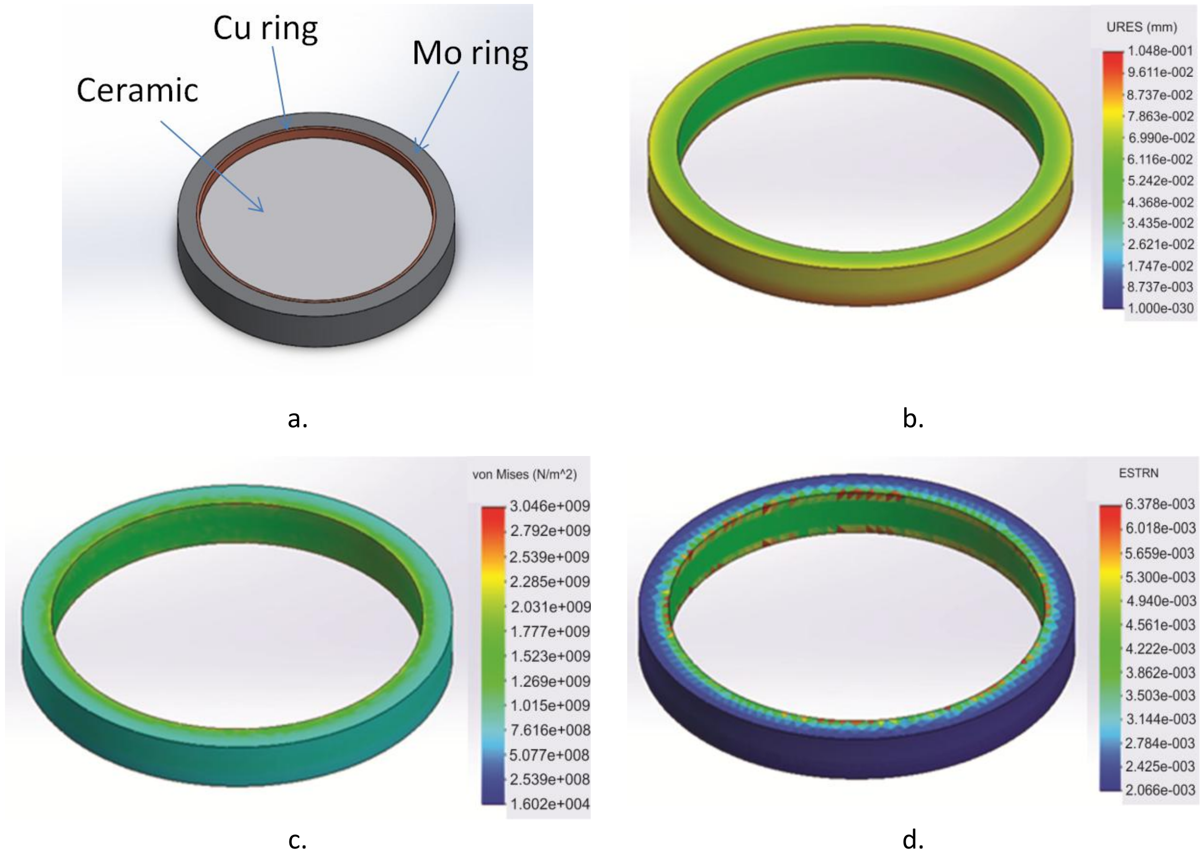


Figure 3.5.1.3.: The main results of ceramic-metal simulation under 850 ^{0}C using Mo ring fixation system.

The thermo-mechanical simulation has been implemented for ceramic disc to Cu ring joint fixing Mo ring under 850^{0}C temperature. The assembling scheme of ceramic disc to Cu ring using Mo ring fixation is presented in the Figure 3.5.1.3-a. The thermo-mechanical simulation results (displacement (b), stress (c) and strain (d)) are shown in the Figure 3.5.1.3.

The maximum displacement value generates the copper ring and it is 0.1mm (Figure 3.5.1.3-b) which is higher than the Mo foil fixation method. The maximum stress level generates the copper-ceramic contact zone and it is 3.046e+0009N/m^2 (Figure 3.5.1.3-c) while the minimum strain generates the copper zone and it is 4.82e-008 (Figure 3.5.1.3-d).

Fabrication difficulties of Mo ring, difficulties for fixation of Cu ring with ceramic disc to Mo ring are the disadvantages of Mo ring fixation method which gives a possibility to receive equal pressure on items under the high temperature conditions.

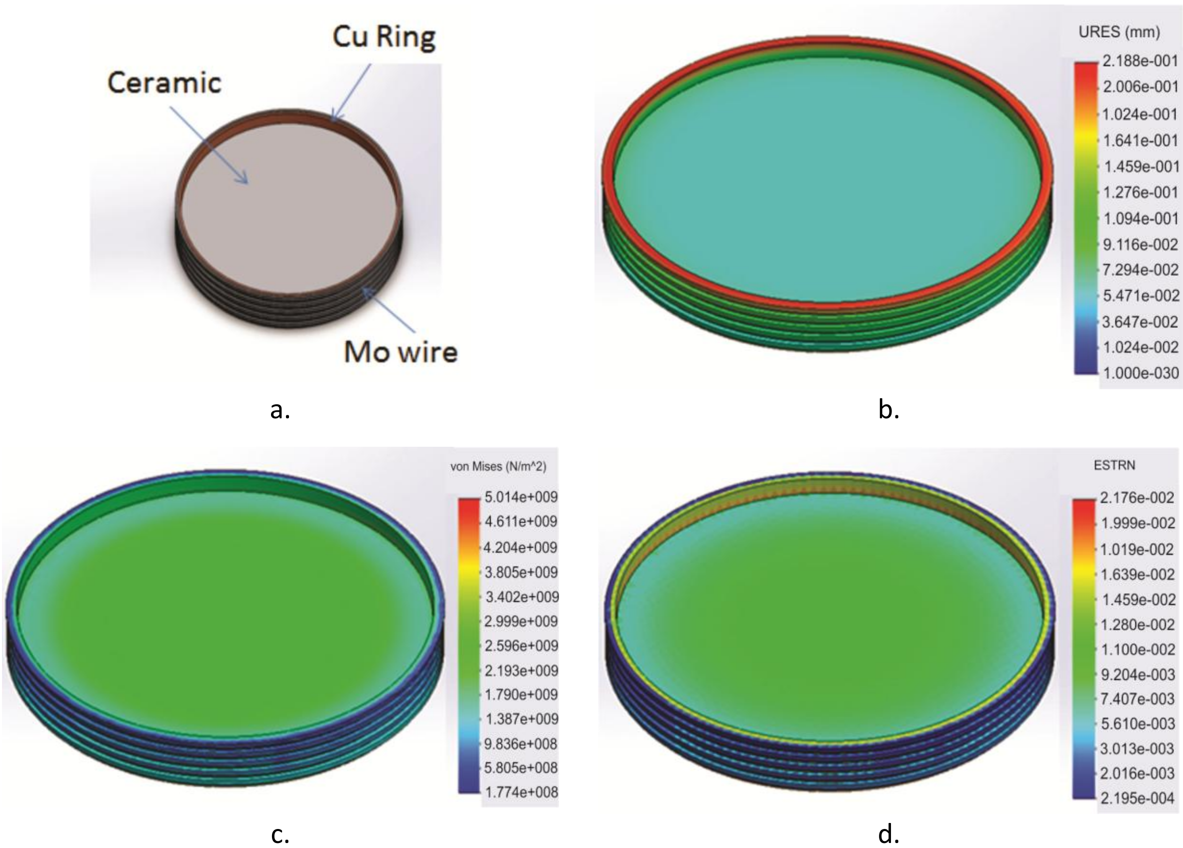


Figure 3.5.1.4.: The main results of ceramic-metal simulation under 850^{0}C using Mo wire fixation system.

The thermo-mechanical simulation has been implemented for ceramic disc to Cu ring joint fixing Mo wire under 850^{0}C temperature conditions. The assembling scheme of ceramic disc to Cu ring using Mo wire fixation is presented in the Figure 3.5.1.4-a. The thermo-mechanical simulation results (displacement (b), stress (c) and strain (d)) through Mo wire fixation are shown in the Figure 3.5.1.4.

The maximum displacement generates the Cu ring and the value is 0.21mm (Figure 3.5.1.4.-b). The maximum stress generates the ceramic material near to copper and the value is 5e+009N/m^2

(Figure 3.5.1.4.-c). The maximum strain generates the copper material and it is 0.02178 (Figure 3.5.1.4.-d).

There are different methods of Mo wire fixation. The Mo wire with 1mm diameter is used during the simulations which can be varied depending on the ceramic and copper geometric shape characteristics.

According to the thermo-mechanical simulation results the Mo wire fixation method is more effective for fixation of ceramic disc to metal ring for brazing compared with other fixation methods (Mo foil, Mo ring, etc.).

3.5.2. The thermo-mechanical simulation of the vacuum break (insulator)

The vacuum breaks are difficult ceramic-metal joints. The thermo-mechanical simulations for 35mm inner diameter vacuum break have been implemented under 850^{0}C temperature conditions using different fixation methods for brazing processes.

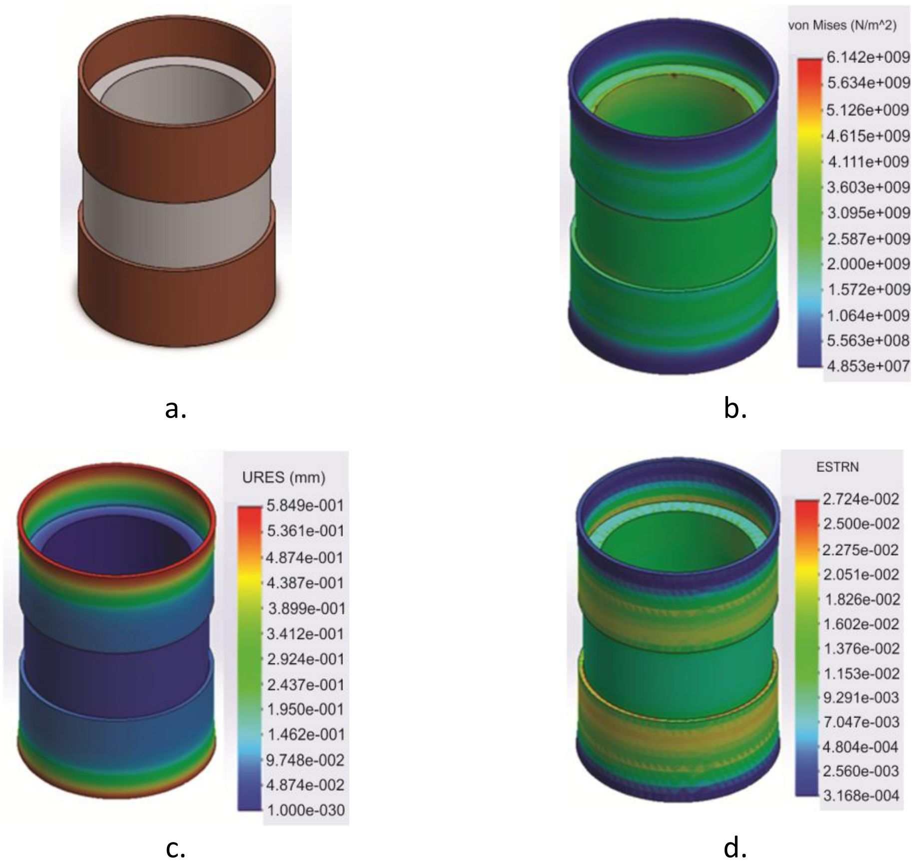
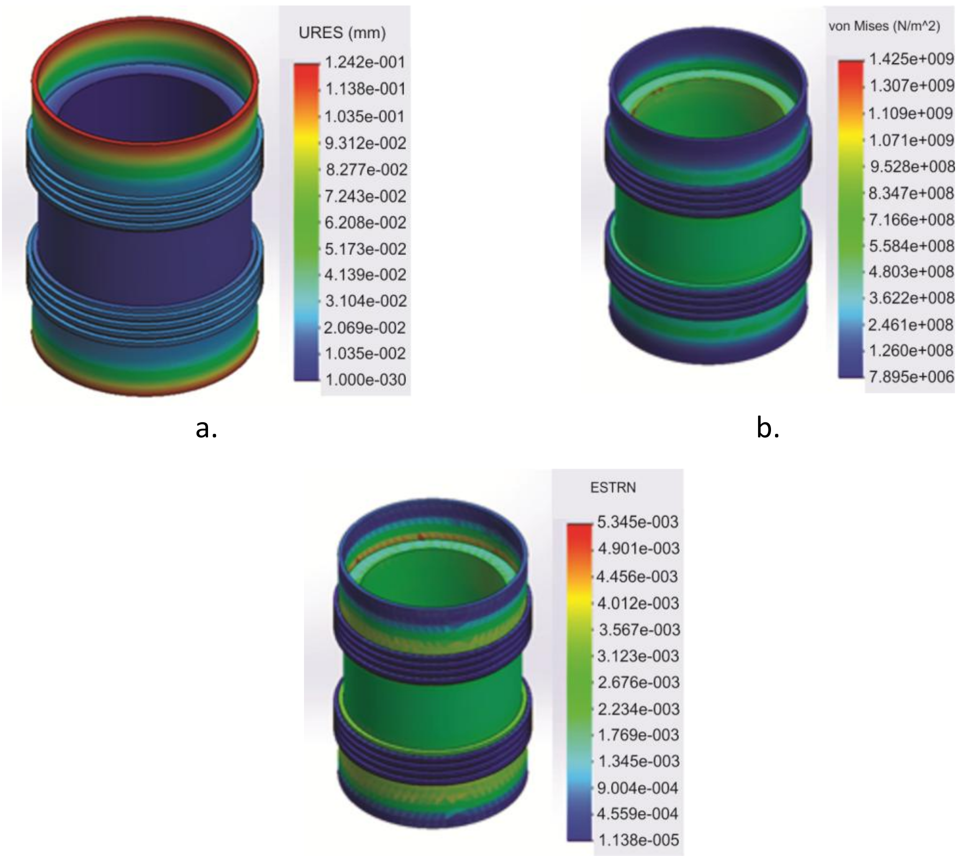


Figure 3.5.2.1.: The main results of the vacuum brake simulation under 850^{0}C.

The first thermo-mechanical simulation has been implemented for vacuum break under 850^{0}C temperature conditions without any fixation mechanism. The vacuum break assembling scheme is presented in the Figure 3.5.2.1-a (the 3D model). The vacuum break consists of a ceramic pipe and Cu pipes.

The thermo-mechanical simulation results (stress (b), displacement (c) and strain (d)) are presented in the Figure 3.5.2.1.

According to the thermo-mechanical simulation results (Figure 3.5.2.1) for pressure effect on the ceramic to metal interlayer zone under the high temperature conditions require materials fixation system.



c.

Figure 3.5.2.2.: The main results of the vacuum break simulation under 200^{0}C

The thermo-mechanical simulation has been implemented for the same vacuum break under 200^{0}C temperature conditions using Mo wire fixation for materials.

The thermo-mechanical simulation results (displacement (b), stress (c) and strain (d)) through the Mo wire fixation are shown in the Figure 3.5.2.2.

The maximum displacement for the joint is 0.12mm (b), the maximum stress value is 1.42e+009N/m^2 (c), the maximum strain value is 0.0053 (d) (Figure 3.5.2.2).

The designed vacuum break can effectively work up to the 200^{0}C temperature conditions according to the thermo-mechanical simulation results.

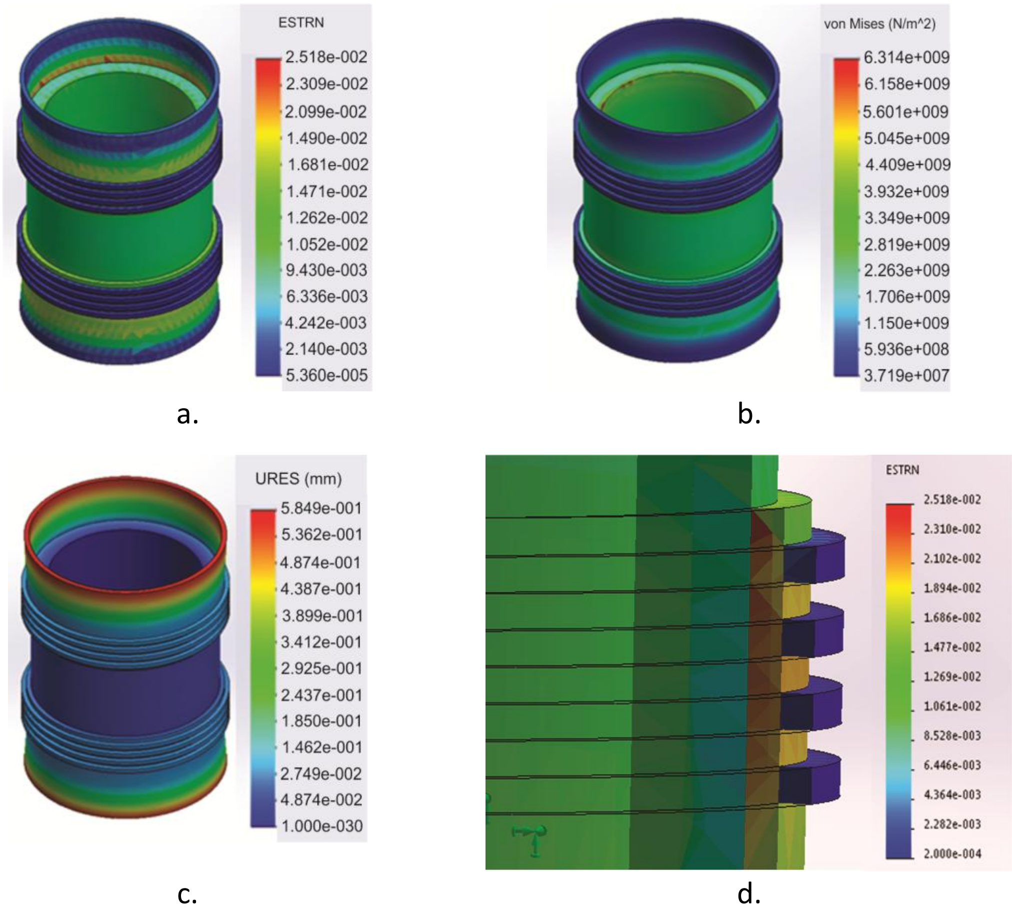


Figure 3.5.2.3.: The main results of the vacuum break simulation under 850^{0}C

The thermo-mechanical simulation has been implemented for the designed vacuum break (the same geometric shape mentioned above) under 850^{0}C temperature conditions using the Mo wire fixation. The main results from the thermo-mechanical simulation (a,d-strain, b-stress and c-displacement) are presented in the Figure 3.5.2.3.

The maximum strain value for the joint is 0.025 (a), the maximum stress value is 6.714e+009N/m^2 (b), the maximum displacement value is 0.584 mm (c) according to the simulation results (Figure 3.5.2.3).

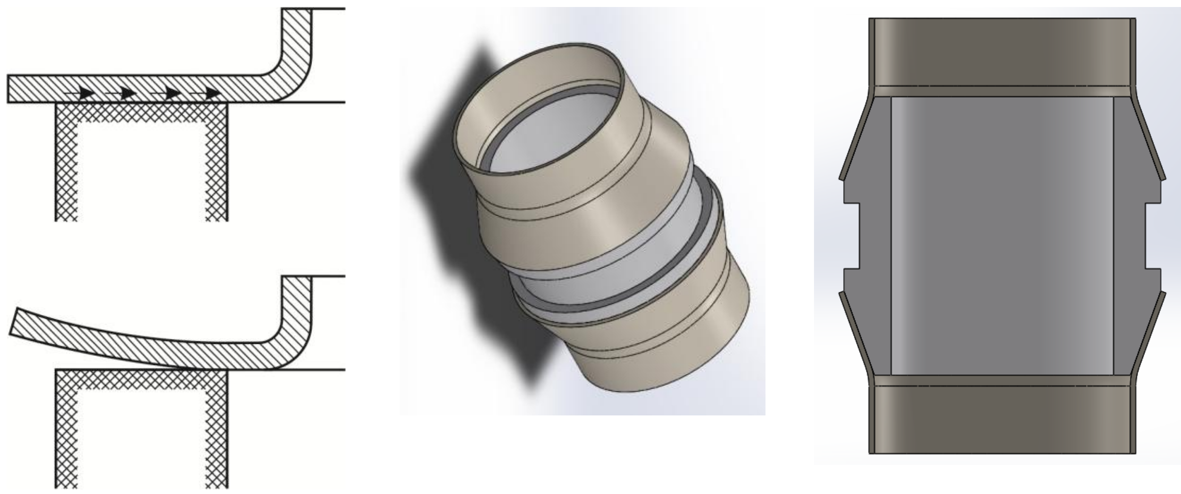
The designed vacuum break can effectively be brazed under the high temperature conditions according to the thermo-mechanical simulations.

3.5.3. The thermo-mechanical simulation of the vacuum break with a conical shape

The vacuum break with a conical shape has been designed. The conical contact zone (brazing zone) reduces the surface stresses during the joint brazing and exploitation.

The high stresses in a smooth surface (Figure 3.5.3.1-a) can damage the joint during the brazing process.

The designed vacuum break structure with a conical contact zone is presented in the Figure 3.5.3.1 (b. 3D model, c. section view).



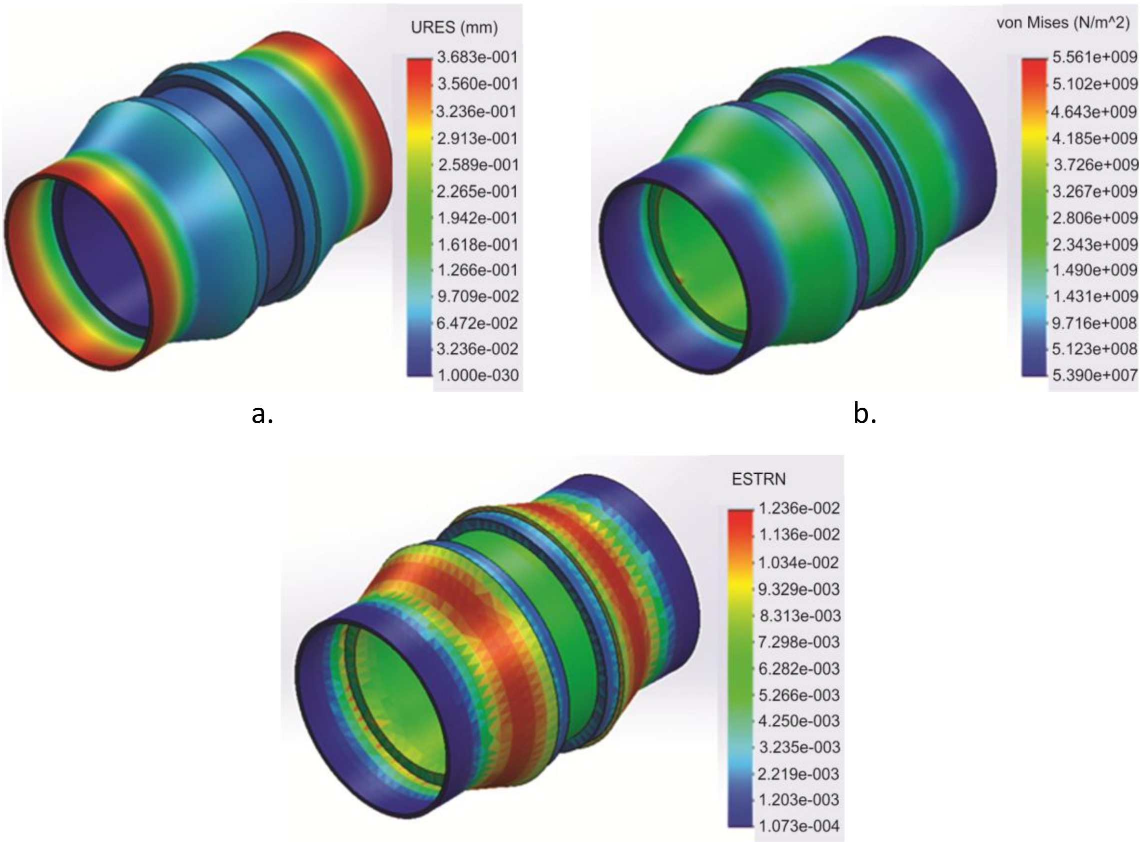
a. b. c.

Figure 3.5.3.1.: The vacuum break with a conical joint zone.

The thermo-mechanical simulation has been implemented for the designed vacuum break under 850^{0}C temperature without any fixation mechanisms. The thermo-mechanical (displacement (a), stress (b) and strain (c)) simulation results are presented in the Figure 3.5.3.2.

The maximum displacement value for the joint is 0.388mm (a), the maximum stress is 5.56e+009N/m^2 (b), the maximum strain value is 0.0123 (c) – Figure 3.5.3.2.

The mechanism requires fixation of the ceramic to metal joint during the brazing process under the high temperature condition according to the implemented thermo-mechanical simulation results.



c.

Figure 3.5.3.2.: The main simulation results of the vacuum break with a conical joint zone.

The fixation mechanism has been designed to fix the vacuum break (conical contact zone) for the brazing process under the high temperature condition. The stainless steel and molybdenum have been selected as fixation materials. The 3D assembled model (a) and section view (b) of designed fixation mechanism are shown in the Figure 3.5.3.3.

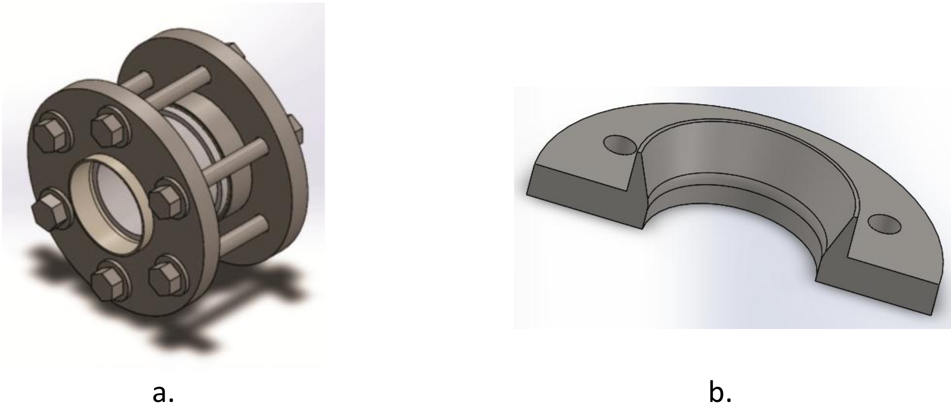


Figure 3.5.3.3.: The 3D model (a) and the section view (b) of the fixation mechanism.

The fixation process is implemented using nuts and screws.

The thermo-mechanical simulation has been realized for the designed vacuum break with a fixation mechanism under 200^{0}C high temperature condition. The section view (a) of the assembled vacuum break with a designed fixation mechanism is presented in the Figure 3.5.3.4.

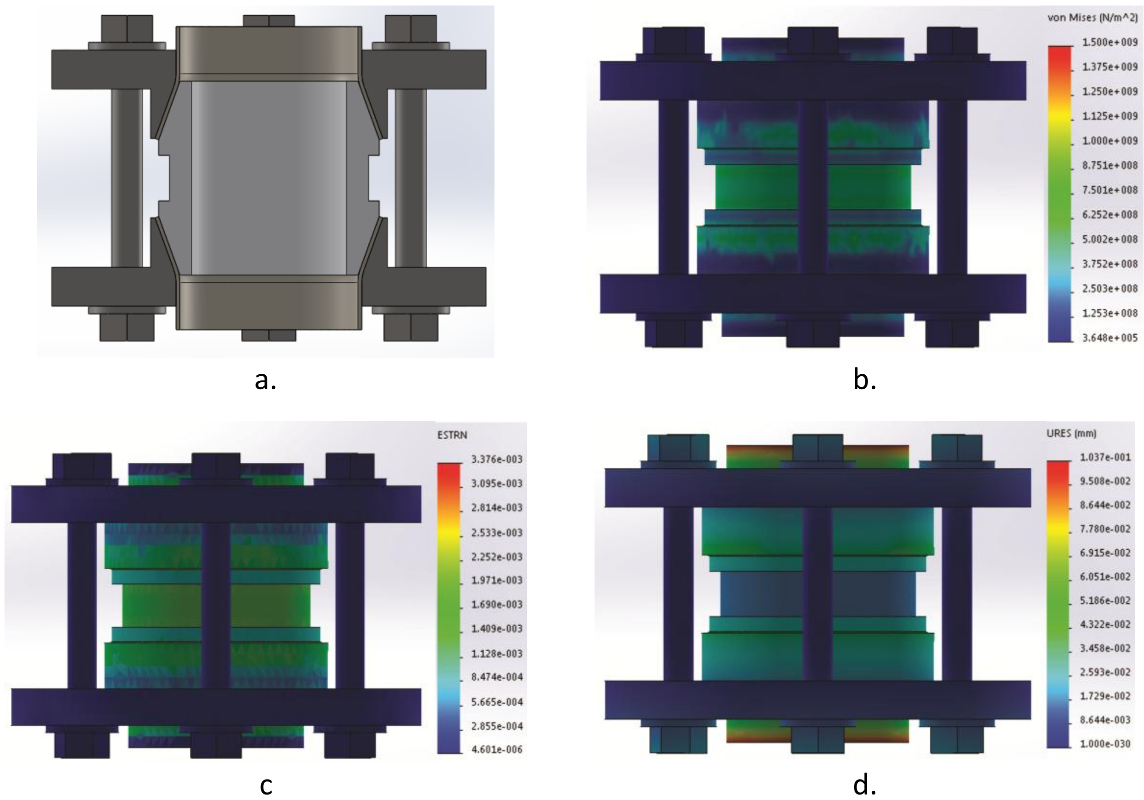


Figure 3.5.3.4.: The simulations results of the vacuum break with a fixation system under 200 ^{0}C.

The thermo-mechanical simulation results (stress (b), strain (c) and displacement (d)) are mentioned in the Figure 3.5.3.4.

The joint can safely warm up to 200^0C temperature with a low stress, strain and displacement level according to the thermo-mechanical simulation results.

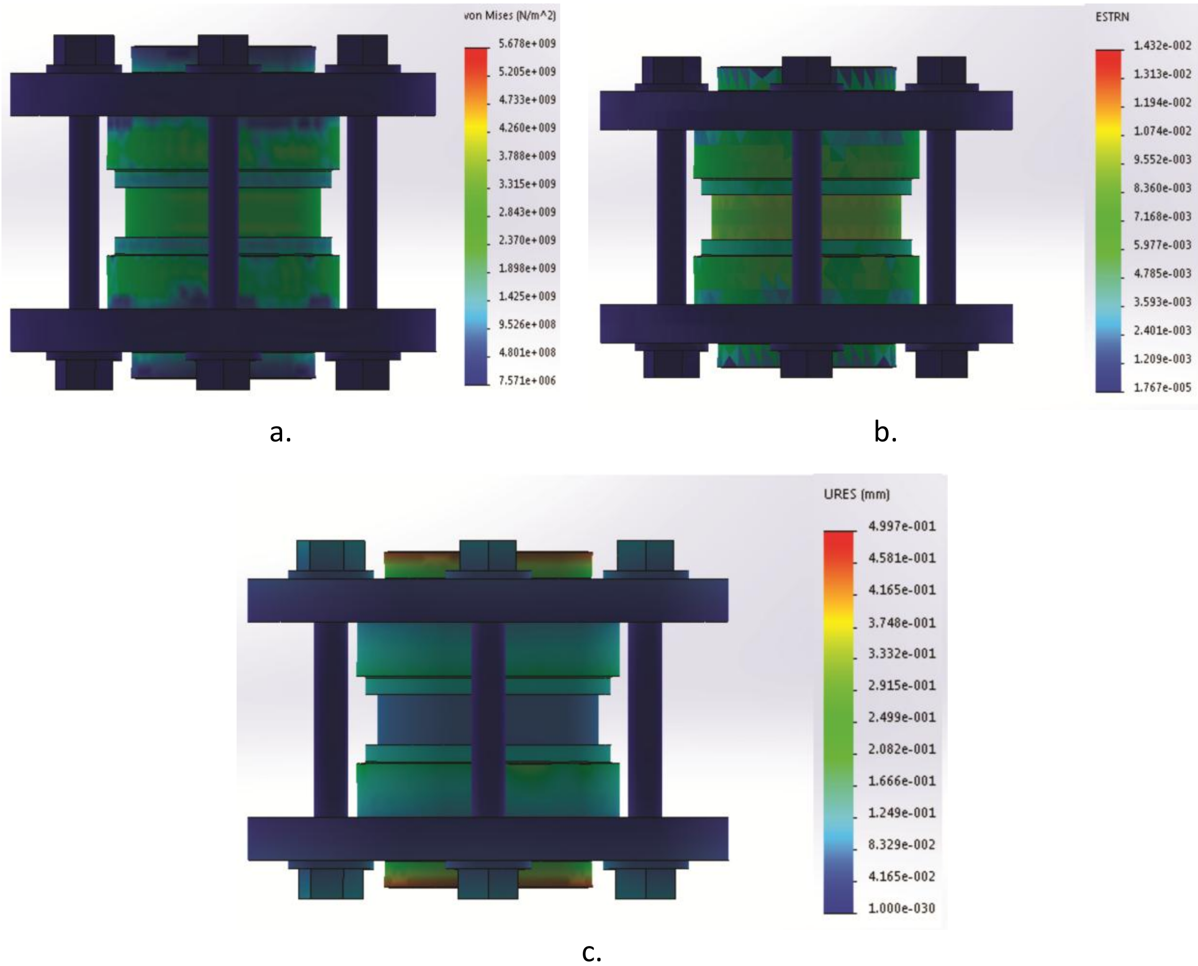


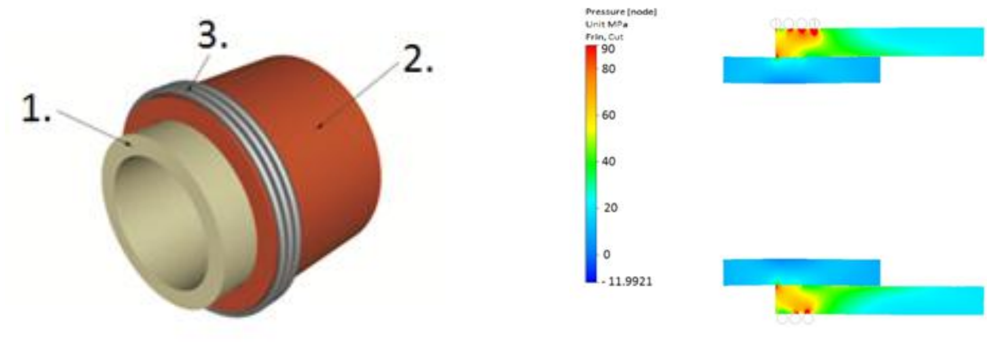
Figure 3.5.3.5.: The simulations results of the vacuum break with a fixation system under 850^0C.

The thermo-mechanical simulation has been realized for the vacuum break with a fixation mechanism under 850^0C high temperature condition.

The thermo-mechanical simulation results (stress (a), strain (b) and displacement (c)) are presented in the Figure 3.5.3.5.

The designed vacuum breaks can be effectively brazed under 850^0C high temperature condition according to the implemented simulation results.

The BN (Boron Nitride) powder can effectively insulate the metal parts of the vacuum break from the fixation systems under the high temperature condition.



a. b.

Figure 3.5.3.6.: The thermo-mechanical simulations based on the Nb wire fixation.

The thermo-mechanical simulation has been done for the cylindrical ceramic – metal fixation based on the Nb fixation. The 3D model (a) and stress (b) of the joint are shown in the Figure 3.5.3.6. [97]

The simulated joint consists of a ceramic (1), a metal (2) and a Nb wire. The simulation has been done under 820^0C temperature condition. The received stress value is high near to the Nb wire (Figure 3.5.3.6-b). The joint can be effectively brazed under the high temperature conditions according to the simulation results.

3.6. The summary of the Chapter 3

- The diffusion brazing new method for dissimilar and difficult geometric shape ceramic to the metal items was developed implementing the pressure differences in the inner and the outer volumes of the items systems. The conical ceramic has been boned with the stainless steel flange based on the diffusion new method. The bonded joint has high quality and high vacuum tightness. The new method gives a possibility to receive equal pressure and flexible regulation of the pressure value on the items system during the brazing process under the high temperature conditions.

- The diffusion bonding new method for bonding (diffusion welding and brazing) cylindrical dissimilar items was developed using different materials coefficient of thermal expansion. The new method warms up local and pressured (fixed) items using electrical current in the fixed wire. The bonding temperature and pressure effect on the items can flexibly regulate changing the electrical current in the fixed wire. The ceramic disc to the Cu pipe has been brazed using the molybdenum-manganese metallization technology based on the new bonding method in the vacuum furnace. The brazed joint has a high quality and it is a vacuum tight.
- The thermo-mechanical simulations have been realized for the ceramic disc to the cylindrical metal using materials different fixation methods brazing under the high temperature conditions (Mo wire, Mo foil, Mo ring). The advantages and disadvantages of the materials fixation methods are mentioned. Taking into account the thermo-mechanical simulation results the Mo wire fixation method is considered as a more flexible and effective method for brazing cylindrical ceramic-metal items.

Chapter 4: The vacuum-tight ceramic-metal joints in the particle accelerators: the vacuum RF windows

The vacuum-tight ceramic-metal joints are widely used in the UHV systems of the particle accelerators. These are particularly used in the kicker magnet's chamber, the insulators, the feedthroughs, various chambers, the beam line windows, the RF windows [98 - 99] and so on. One of the most interesting, complicated and important vacuum tight ceramic-metal joints in the particle accelerators are the vacuum RF windows.

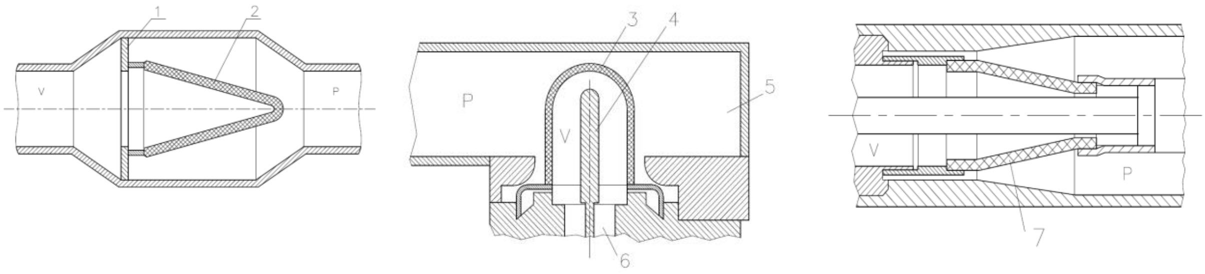
4.1. The variety of the vacuum RF windows

There are many different types of vacuum RF windows and they are divided based on the electromagnetic wave characteristics (frequency, power, etc.) and the inner shape as well as the mechanical structure. The mechanical structural design of the RF windows depends on the parameters of the electromagnetic waves, and especially on the frequency. According to the frequency, the RF windows are categorized into S-band, L-band, C-band, X-Band, K-Band, etc. [100]. The dimensions of the waveguides are accordingly varied depending on the RF frequency. Standard sizes of some rectangular waveguides are presented in the Table 4.1.1.

Frequency band name	Frequency (GHz)	Size (mm)	Waveguide name
L-Band	1.15 — 1.72	165.1 × 62.55	WR650
S-Band	2.60 — 3.95	72.14 × 34,94	WR284
C-Band	3.95 — 5.85	47.55 × 22.2	WR187

Table 4.1.1: The standard sizes of some rectangular waveguides.

Generally there are three types of RF windows – the waveguide type, the coaxial type and the waveguide coaxial [101]. Each type of the RF window is designed for a special purpose [102-104]. The schematic views of the RF window types are shown in the Figure 4.1.1, where the left panel shows a waveguide type RF window, the middle panel shows a waveguide-coaxial type RF window and the right panel shows a coaxial type RF window [51].



a. b. c.

Figure 4.1.1: The schematic views of RF window types.

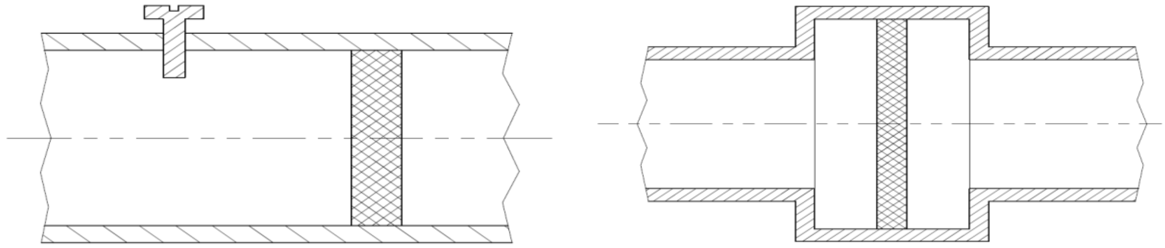
The ceramic dielectric materials (denoted by numbers 2,3,4 in Figure 4.1.1) divide the sides with vacuum (V) from the side with pressure (P) in the corresponding RF windows.

Depending on the special requirements, the RF windows can have different mechanical structures. Generally the RF windows have the following common structural components (again, see Figure 4.1.1):

1. diaphragm,
2. conical window,
3. hemispherical window,
4. antenna,
5. waveguide,
6. coaxial line,
7. conical section shape window

The RF parameters are different before and after the RF window. The main reasons for this are the RF power losses in the dielectric material (i.e. various components are warming up) and the RF reflection.

The different shapes and technological solutions of the vacuum RF windows [105] have been calculated and designed to minimize the RF losses and to maximize the effective throughput of the electromagnetic waves. The combination of the corresponding effective inner geometric shape and the type of the material of the vacuum RF window can significantly decrease the RF power losses and reflections.



a. b.

Figure 4.1.2: The schematic views of the RF windows.

The rectangular and the pillbox types of the RF windows are presented in the Figure 4.1.2. The rectangular RF windows can be with and without regulation parts (for example the screws can be used as a regulation item - Figure 4.1.2-a [106]) depending on the working environment. The screw-based regulation of the waveguide is not widely used in the advanced accelerators.

According to the literature review, one of the effective and reliable types of the RF windows is the vacuum pillbox type RF window (Figure 4.1.2-b).

4.2. The pillbox type RF windows

A variety of the pillbox type RF windows are widely used in the advanced acceleration complexes. Based on the frequency the pillbox type RF windows can be divided into S-band, C-band and more. The section view of the designed pillbox type RF window (schematic view) is presented in Figure 4.2.1. The developed schematic 3D model is the first step of the mechanical design of an RF window (see Figure 4.2.1). The designed 3D model gives a possibility to understand the basic structure, the design, the necessary steps for the fabrication procedure, the installation and the operation specifications of the RF window.

Generically, the pillbox type RF windows consist of a dielectric disc (1) which separates the RF window into two sections – the vacuum side (a) and the pressured side (b). In the pressured side the RF window assembles into the waveguide line which connects with klystron. The metal flanges (6) are used to assemble the RF window. Some inert gases like N_2, SF_6 are used in the pressured side. The ceramic disc is fixed to the inner cylinder (2) using different methods – brazing, thermo-compression welding. The cylinder with dielectric disc joins two other cylinders (3) and creates the pillbox shape. All these cylinders are joined with outer cylinder (7) for an enhanced mechanical strength and for cooling (c). The pillbox shape covers two ends and connects rectangular waveguide (5) through the cover plates (4).

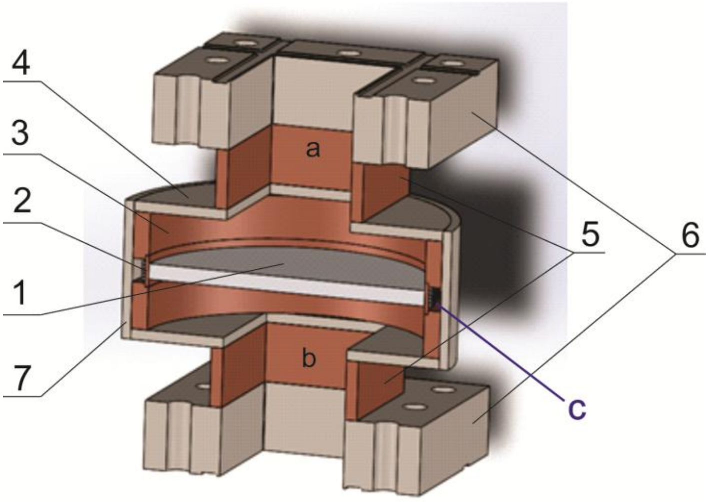


Figure 4.2.1.: The section view of the pillbox type RF window (schematic view).

The schematic view (Figure 4.2.1.) will give a possibility to create requirements for the development and design of the RF window (an electro-magnetic design, a mechanical design, brazing technologies etc.).

4.3. The requirements for the Pillbox type RF windows

In order to avoid dangerous situations and to increase durability of the RF window it is necessary to consider all the requirements including the design, the fabrication, the installation and the operation activities.

Generally the new design and fabrication of the high quality vacuum RF window are divided into several different steps presented below.

- The desired required characteristics – required documentation (the RF parameters, vacuum and pressure levels, etc.);
- The electro-magnetic design (the calculation, the simulations for the inner geometric shape and the corresponding effective materials);

- The mechanical and thermal design (developing of the effective mechanical structure and drafting – including development of the material brazing and the welding technologies, the items machining specifications, the heat removal cycle design – the thermoregulation systems, etc.);
- Selection of the corresponding materials;
- The machining (rough & fine) of the system parts based on the developed and designed technologies and drawings;
- Surface preparation – treatment (cleaning, polishing, etc.);
- Precise assembling;
- Brazing and welding in corresponding accuracies (diffusion brazing and welding, thermo-compression welding in a vacuum or an inert gas environments);
- UHV test – residual gas analyzing, leak detection under the high temperature conditions;
- Tuning;
- Pre-processing;
- High power conditioning;
- Conditioning under the RF;
- Operation in real working environments – under the high RF power, UHV, pressured gas and cooling conditions;

Generally the design of the RF window is divided into three main parts. The first is the general requirements part where the main parameters of the electromagnetic waves and the specific parameters of the RF window are calculated and simulated.

The second design part of the RF window is the electro-magnetic design based on the main requirements (first design part) which gives possibility to define the effective inner shapes and the materials of the RF window and it is followed by the mechanical and thermal design of the RF window based on the electromagnetic design results. This design parts include the development of the effective mechanical structure, brazing and welding technologies.

The first designed schematic view of the RF window is important (Figure 4.2.1.) to understand the main designing problems including the corresponding materials selection, the developing brazing technologies, the mechanical structure stabilities, the effective thermoregulation.

Based on the design documentation of the fabrication processes – mechanical machining of the separate items, polishing, coatings, mechanical measurements, brazing and welding are followed.

The final steps are testing procedures. There are many testing procedures to evaluate the quality of the RF windows. The He leak detection and RGA are used to evaluate the vacuum tightness and the residual gas properties.

The thermo-mechanical tests evaluate the window stability under the mechanical and thermal effects.

The final test is the simultaneous testing of the window under the high power RF, UHV, pressured gas, thermoregulation condition.

The design requirements of the vacuum RF window can be varied depending on the working conditions.

The dielectric disc must have as high transparent level as possible for electromagnetic waves. Alumina and beryllia ceramics are widely used as dielectric discs in the RF window. Alumina ceramic has high mechanical strength and low thermal conductivity in comparison with beryllia.

The content, the homogeneity, the thickness and the surface characteristics are the main descriptions of ceramics for the vacuum RF window.

The ceramics must have high electrical strength which can avoid from a breakdown of RF window under the high RF power.

To satisfy the vacuum RF window requirements it is necessary to develop and design new special technologies including precise vacuum brazing technology.

The important requirements for the RF windows are presented below.

- High mechanical strength;
- High transparent level for the electro-magnetic waves;
- Low secondary electron emission;
- High conductivity of walls (metal);
- Reliability and durability;

- Outgassing low level;
- High reproducibility;
- High level of homogeneity of materials structures;

Materials joints in the RF window must be precise, reliable, reproducible, effective, low magnetic features, high homogeneity, thermal shock resistance, low gas penetration, low outgassing level depending on the temperature, low adsorption characteristics.

The many joints of the vacuum RF windows are ceramic to copper, copper to stainless steel, copper to copper, stainless steel coating technologies. Copper is more suitable material for the inner side of the RF window which has high surface conductivity and thermal conductivity.

During the ceramic to copper joint design it is important to take into consideration the joint operational temperature.

4.4 The pillbox type RF window – mechanical design

4.4.1 Materials for the pillbox type RF window

The brazed RF windows have many advantages like mechanical stability, easy installation and maintenance [107,108].

The pillbox type vacuum RF window (S-band) has been mechanically designed [109].

The schematic section view of the mechanically designed RF window is presented in the Figure 4.4.1.

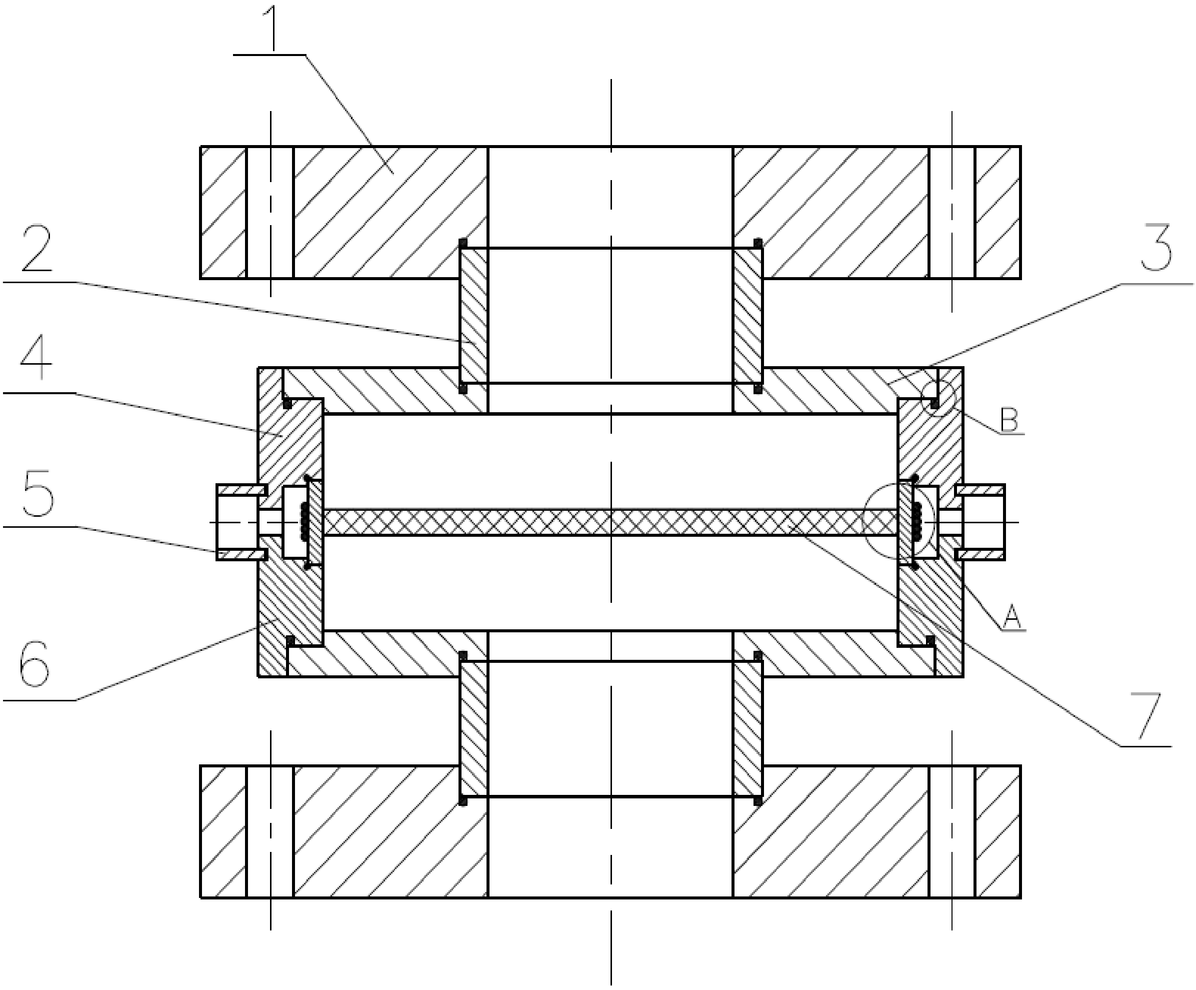


Figure 4.4.1.: The section view of the mechanically designed RF window.

The inner value of the window is divided into two parts – UHV and pressured gas by ceramic disc (7). The ceramic thickness depends on the throughput level of electromagnetic waves, the mechanical strength of ceramic and joint.

For the effective operation of the vacuum RF window the thickness of the ceramic disc must not be thin and thick.

The 4mm ceramic disc was selected for the design.

The main components of the pillbox RF window are presented in the Figure 4.4.1. The main components of the RF window are the flanges (1), the waveguides (2), the pillbox covers (3), the cupper cylinder (4) and the inner cylinder (6), the cooling input and the output pipes (5) and the ceramic disc (7).

1. The 316LN stainless steel was selected as a material for the flanges. The 316LN SS has a high mechanical strength, a low magnetic permeability, a high machinability, a coating ability and can effectively be used in the RF windows. The flanges have been mechanically designed for the WR284 waveguide standard.

2. The oxygen free high conductivity (OFHC) copper was selected as a waveguide material. The OFHC copper has high electrical and thermal conductivity and majority S-band waveguides materials are OFHC copper.

3. The 316LN stainless steel with coated copper in the inner surface was selected as a cylinder cover material.

4. The OFHC copper was selected as a cylindrical ring material.

5. The 316LN stainless steel was selected as a fitting for input and output cooling water. The stainless steel is inert material for water and is used for the RF window cooling.

6. The OFHC copper was selected as a cover material.

7. The 99.7% alumina was selected as a ceramic ring.

The 316LN stainless steel for a high surface conductivity needs inner surface coating in copper. The electrochemical and PVD methods can be effectively used for high quality copper coating on a stainless steel surface [110].

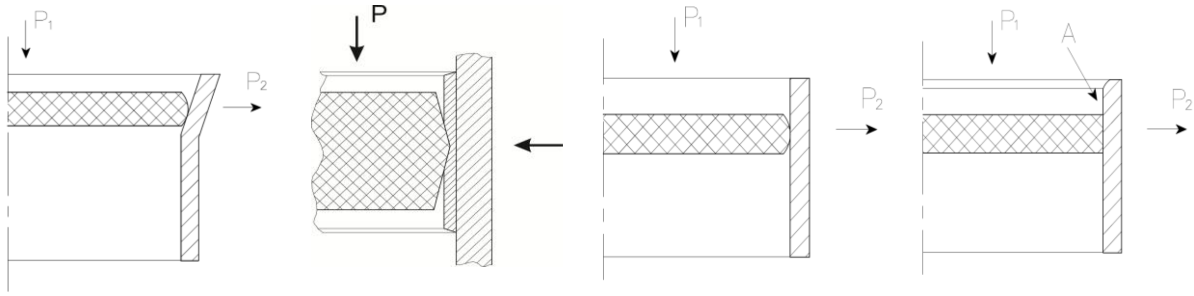
The Beryllia ceramic has higher thermal conductivity than alumina [111].

The geometric shape of the mechanical designed RF window is preliminary and for precise geometric shape an additional electro-magnetic simulationis necessary.

Depending on the electromagnetic design of the RF window the Kovar can be used as a RF material.

4.4.2. Brazing of the ceramic disc to metal ring for the RF window

One of the difficult and important joints of the RF window is brazing the ceramic disc to the metal ring.



a. b. c. d.

Figure 4.4.2.1: The section views of the cylindrical ceramic to metal fixation (problematic zones).

The fabrication of ceramic disc to copper ring systems is difficult process and includes the following steps –the fabrication of alumina disc and copper ring, the fixation of the ceramic disc to the copper ring.

The fixation of the ceramic disc to the Cu ring is difficult process (assembling difficulties is shown in the Figure 4.4.2.1.) and the assembling specifications are described below.

a. The ceramic disc has higher diameter than the Cu ring. In this case the fixation is impossible.

b. The fixation ceramic disc to the Cu ring with solder is difficult but possible.

c. The effective fixation way is the fixation of ceramic with chamfer or fillet. In this case the contact area for the ceramic disc to the Cu ring is low and it is undesirable for the future brazing.

d. The fixation of the ceramic disc to the Cu ring using corresponding tolerance in the items.

According to the fixation evaluations the sizes of alumina and ceramic items must be in corresponding tolerances for an effective fixation.

For an effective brazing procedure the contact area of ceramic and copper must be as high and hermetic as possible (without any chamfers and fillets).

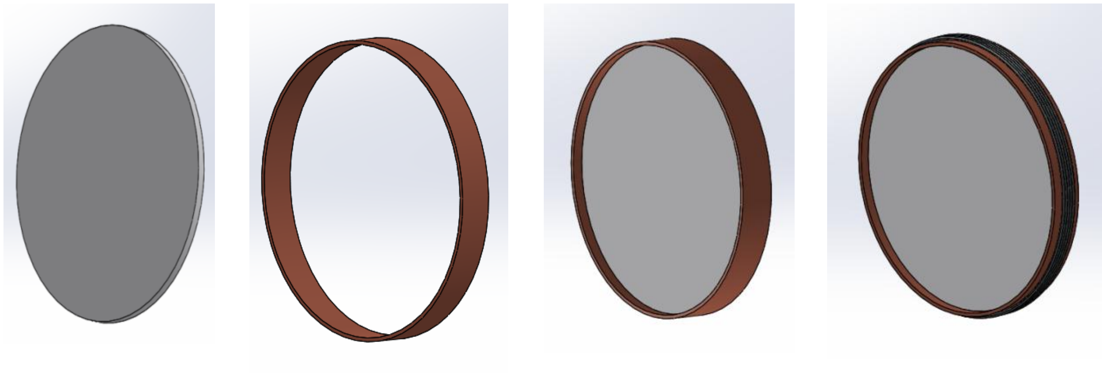
Three main methods can be used to fix solder in the ceramic disc to the copper cylinder.

1. Using thin foil solder;
2. Using solder wire in the upper side of the ceramic ring which is fixed horizontally;
3. Using coating solder in the ceramic side surface.

Before the items fixation it requires a metallization in the ceramic surface (Mn-Mo+Ni).

The ceramic disc to copper ring assembling scheme is presented in the Figure 4.4.2.2.

The ceramic disc (a) is moved into the middle of Cu cylinder (b) and received assembly (c) is fixed by the Mo wire (d).



a. b. c. d.

Figure 4.4.2.2.: The ceramic disc to the copper ring assembling scheme.

Solder quantity and solder fixation in the joint are one of the important points of the brazing processes. The developed solder fixation solutions are presented in the Figure 4.4.2.3 and described below:

a. The solder wire (3) is placed in the upper surface of the ceramic (1) and near surface of the Cu ring (2). The solder is placed before fixation with Mo wire (4). This fixation method is easy but solder wetting in alumina to the copper contact zone will be difficult during the brazing process. The disadvantage of the method is the solder low wetting on ceramic to Cu interlayer surface.

b. In this case thin solder sheet is used (it can also be coated solder surface or mechanically hermetical fixed sheet) (3) between ceramic (1) to Cu (2) ring being fixed by the Mo wire. This method can give possibility to braze hermetically the ceramic to the Cu with maximum contact area.

- The usage of the special grooves is another method to fix the solder. In this case the contact area is small in the ceramic to Cu interlayer zone.

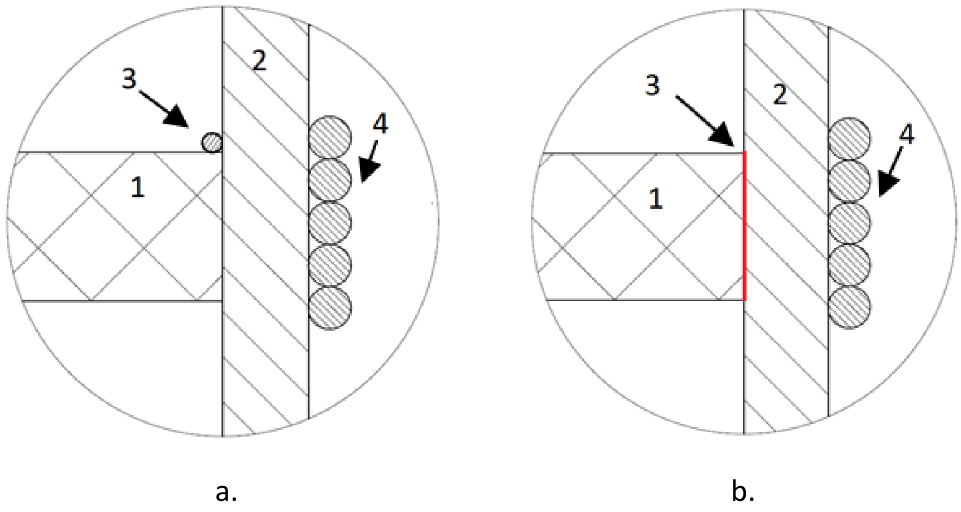


Figure 4.4.2.3.: The solder fixation method for an effective brazing

The ceramic disc to the Cu ring fixation using Mo wire is presented in the Figure 4.4.2.4 and described below.

a. Before brazing process the ceramic (1) is fixed to the Cu (2) joint using the Mo wire (3).

b. During brazing process under the high temperature conditions the Mo wire (3) deforms the Cu cylinder (2) and it gives possibility to press the Cu cylinder to the ceramic disc (1). This is an effective method which provides an effective brazed joint.

c. The combination of Mo wire (4) and Mo foil (3) will be an effective fixation to avoid from the deformation of the Cu cylinder (2) to fix the ceramic disc (1).

The method (using the combination of the Mo wire and foil, ring) can decrease the deformation level in the Cu cylinder.

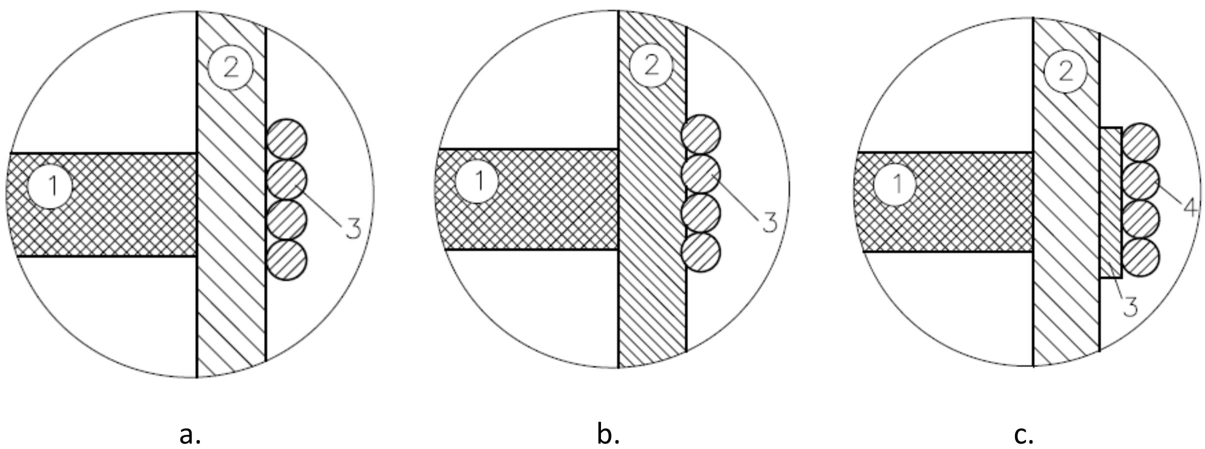


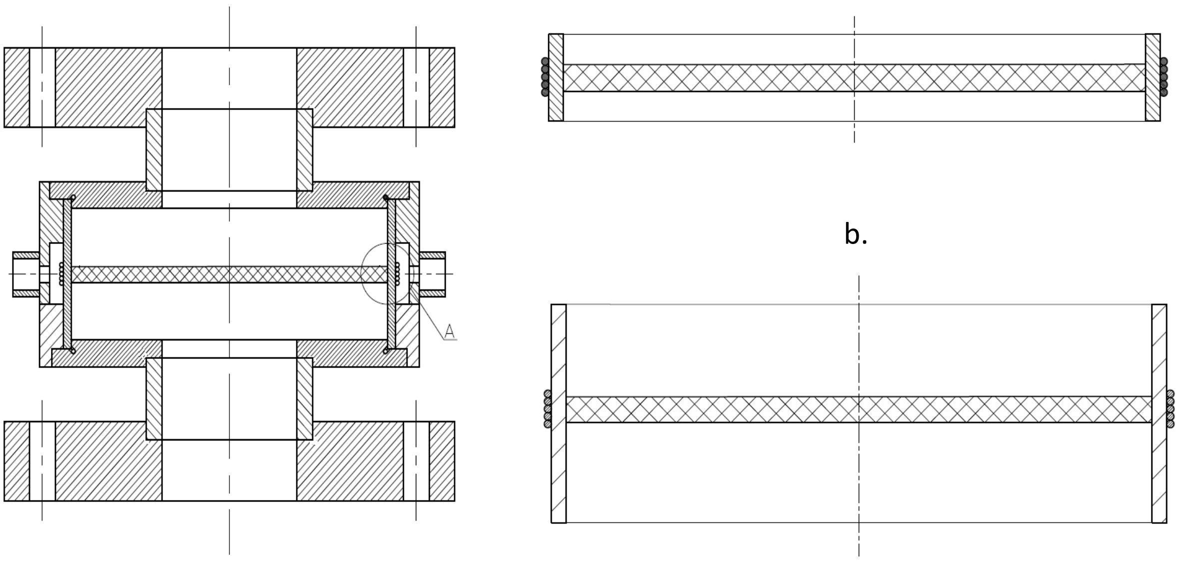
Figure 4.4.2.4.: The ceramic ring to the copper cylinder fixation.

These fixation methods can effectively be used for different kind of materials.

The mechanical structure of the vacuum RF window has been designed and the section view is presented in the Figure 4.4.2.5.

In case of the ceramic disc to the long Cu cylinder fixation two brazing zones are reduced from the window (Figure 4.4.2.5-a) but the precise fixation problem for the items increases (Figure 4.4.2.5-c).

In case of the ceramic disc to the short Cu cylinder fixation the items fixation can be easily realized but the additional grooves for solder are required for the brazing (Figure 4.4.2.5-b).



b.

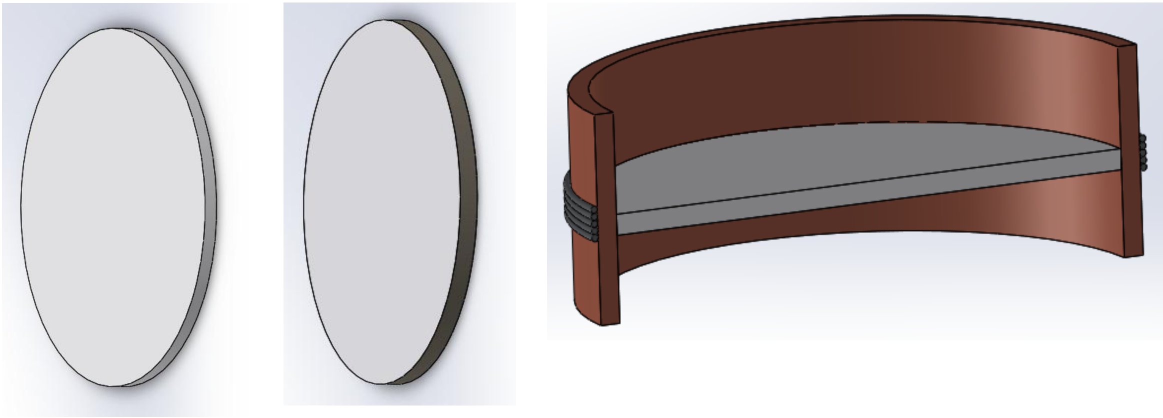
a. c.

Figure 4.4.2.5.: The RF windowschematic view.

The requirements for surface characteristics of the Cu cylinder (roughness) depends on the electromagnetic calculation of the RF window.

The fixation scheme of the ceramic disc to a long Cu cylinder is presented in the Figure 4.4.2.6.

Before the items fixation the ceramic disc (a) has been metallized and Ni plated (b), afterwards the corresponding solder is assembled with the Cu cylinder (c).

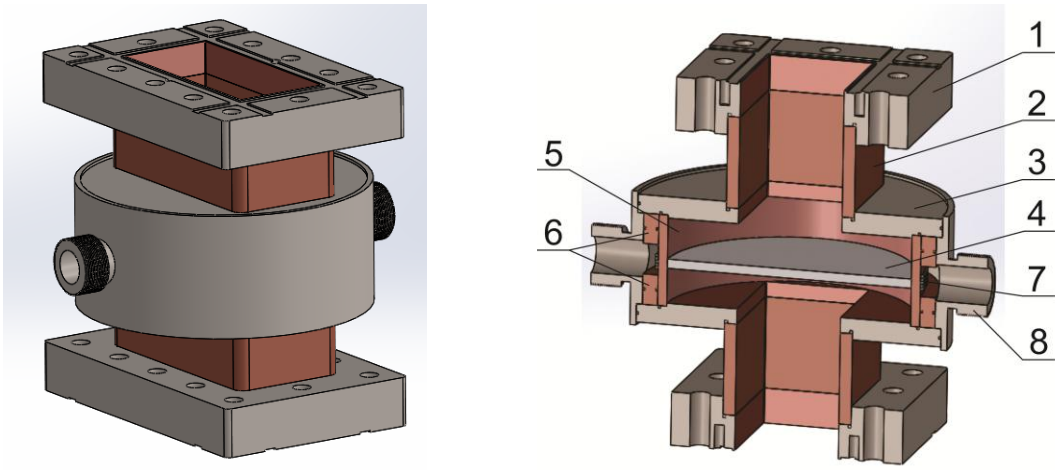


a. b. c.

Figure 4.4.2.6: The fixation scheme of the ceramic disc to a long Cu cylinder.

4.4.3. The RF window brazing

The RF window brazing can be implemented with a step (one brazing process) under the high temperature conditions. According to this method it is difficult to receive a high quality joint.



a. b.

Figure 4.4.3.1.: The 3D model (a) and the section view (b) of S-band pillbox RF window.

The mechanical designed pillbox RF window is presented in the Figure 4.4.3.1.

The RF window consists of the flanges (1), the waveguides (2), the pillbox covers (3), a ceramic disc (4), a pillbox cylinder (5), the fixation rings (6), a fixation Mo wire (7), the water input and output fittings (8).

The precise technological project requires the RF window brazing implementation with a process including some experimental investigations. This process implementation requires one type solder.

The RF window separated items brazing can be implemented using several solders under the different melting temperature.

The designed brazing technology for the RF window consists of several steps which are presented below.

1. Brazing the window pill box type part;
2. Brazing the flanges to the waveguides;
3. The final brazing of the RF window.

1. The section view of the window pill box type part is presented in the Figure 4.4.3.2. Before that it is required a metallization of the ceramic disc (1) and TIG welding of outer cylinder (4) to the water input and output fittings (5). The window pill box type part consists of a ceramic (1), an inner Cu cylinder (2), fixed Cu cylinders (3), an outer cylinder (4) and the water input and output pipes (5). The precisely assembled joint can effectively be brazed under the vacuum and high temperature conditions.
2. The window second brazing part is presented in the Figure 4.4.3.3-a which consists of the stainless steel flanges (1), the Cu waveguides (2) and the pill box covers (3). The items have special grooves for solder. The pill box cover (Fig. 4.4.3.3-b) is stainless steel with a Cu coated in the inner side. The brazing can be implemented with one process under the high vacuum and high temperature conditions using Pacusil solder.
3. The third brazing process is the implementation of the first (pill box type part) and the second (waveguide with flange) parts of the window with one process using Ag72-Cu28 solder (Figure 4.4.3.3).

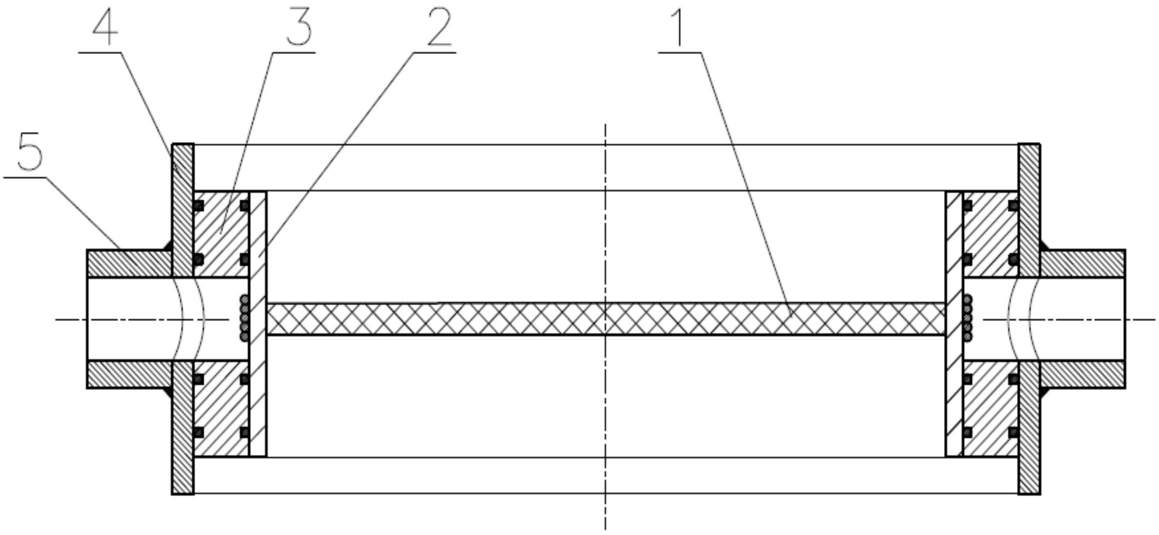
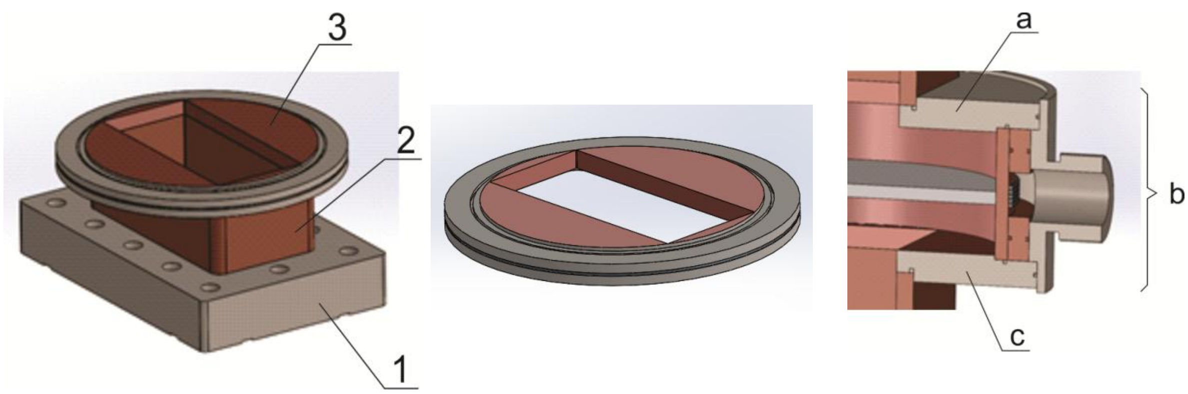


Figure 4.4.3.2.: The ceramic disc to the Cu cylinder brazing.

This method will be more efficient in the case of the several RF windows fabrication. The precise fixation of all items and joints are important before the brazing procedure. The precision tolerance of the items is the most important part for the precise fixation.



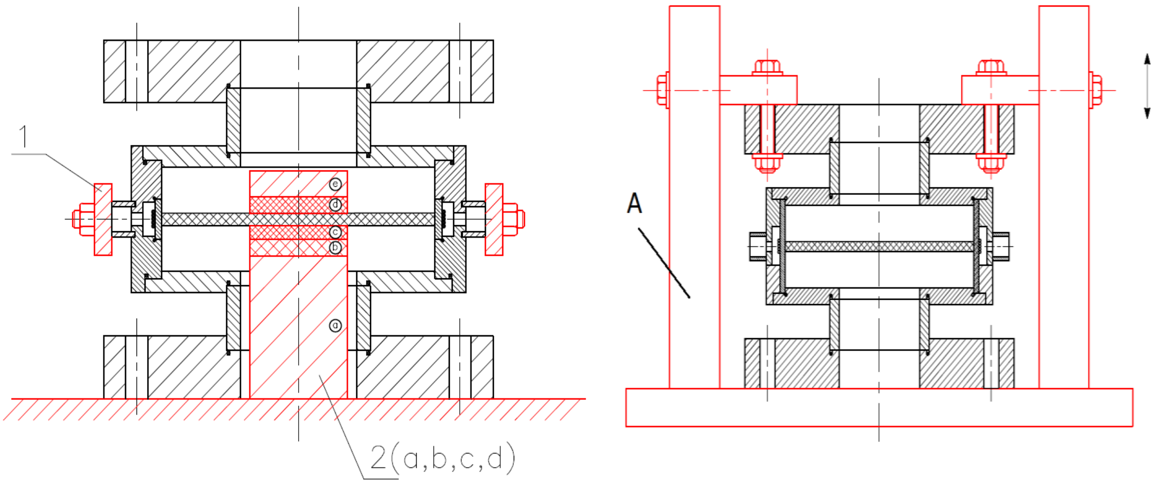
a. b. c.

Figure 4.4.3.3.: The RF window brazing scheme.

Different kinds of pins can be effectively used for the fixation of the window flanges in one precise direction.

The RF window items precise fixation is very important during the diffusion brazing process.

The fixation methods have been designed for the RF window fixation during the brazing process under the high temperature brazing conditions.



a. b.

Figure 4.4.3.4.: The fixation of the materials for a diffusion brazing.

The fixation methods are presented in the Figure 4.4.3.4 (red color).

The first fixation system (Figure 4.4.3.4-a) consists of an outer (1) and inner fixation part (2). The outer fixation part is fixed to the water input and output fittings and consists of two plates and bolts, nuts and washers. The inner fixation part is fixed to ceramic disc and it consists of several parts (a,b,c,d,e). The fixation parts of near to the ceramic (c and d) have similar coefficient of thermal expansion for effective cooling down during the brazing process. The fixation parts (a,b,c,d,e) are used to receive a high parallelism of ceramic disc during the brazing process.

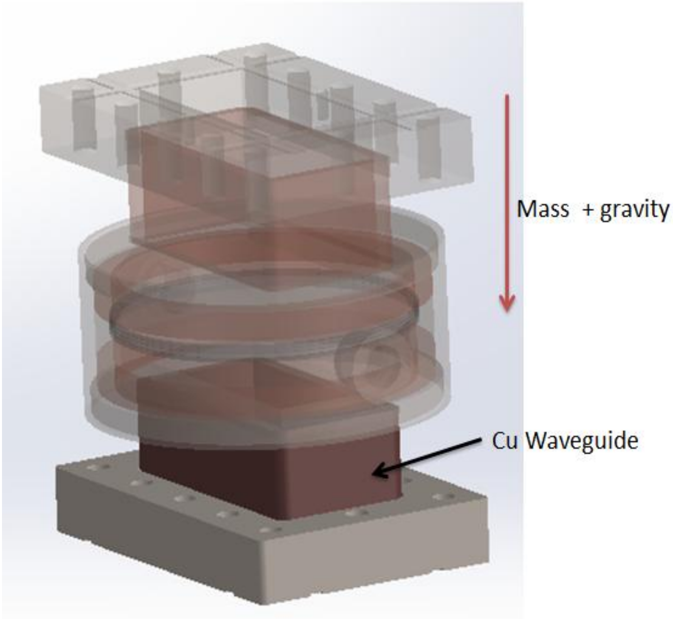
The second fixation system is presented in the Figure 4.4.3.4-b. The fixation mechanism is shown in red color-A. The developed system gives an opportunity to fix the RF window from the outer side without using any pins and other fixation systems.

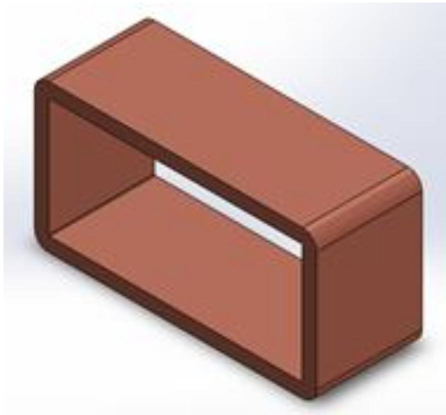
The developed and designed fixation systems can effectively be used to braze the RF window under the high temperature conditions.

4.5. The mechanical and thermal simulation of the waveguide for the RF window brazing process

The geometric shape accuracy of the RF window components is important under the high temperature brazing condition for an effective brazing process. The waveguide is one of the important RF window components.

The thermo-mechanical simulation has been done for the RF window waveguide under 800^{0}C high temperature conditions.





a. b.

Figure 4.5.1.: a. the waveguide in the RF window, b. the waveguide shape.

The waveguide in the RF window (a) and the waveguide shape (b) are presented in the Figure 4.5.1. The material of the waveguide is Cu. The weight of waveguide is 3.4kg.

The simulation is implemented under the 15kg mass effecting on the waveguide. The mass of the Cu waveguide is 239.85g.

The simulation has been implemented in a static regime.

The thermo-mechanical simulation results (stress (a), the displacement (b) and the strain (c)) are presented in the Figure 4.5.2.

The maximum stress value for the waveguide under 800^{0}C temperature condition is 3.39096e+009 N/m^2 (Figure 4.5.2-a).

The maximum displacement value in the waveguide is 0.039mm (Fig. 4.5.2-b). The maximum strain value is 0.0065 (Figure 4.5.2-c).

According to the thermo-mechanical simulation results the waveguide can effectively be brazed under 800^{0}C temperature and under 15kg mass conditions as a part of the vacuum RF window.

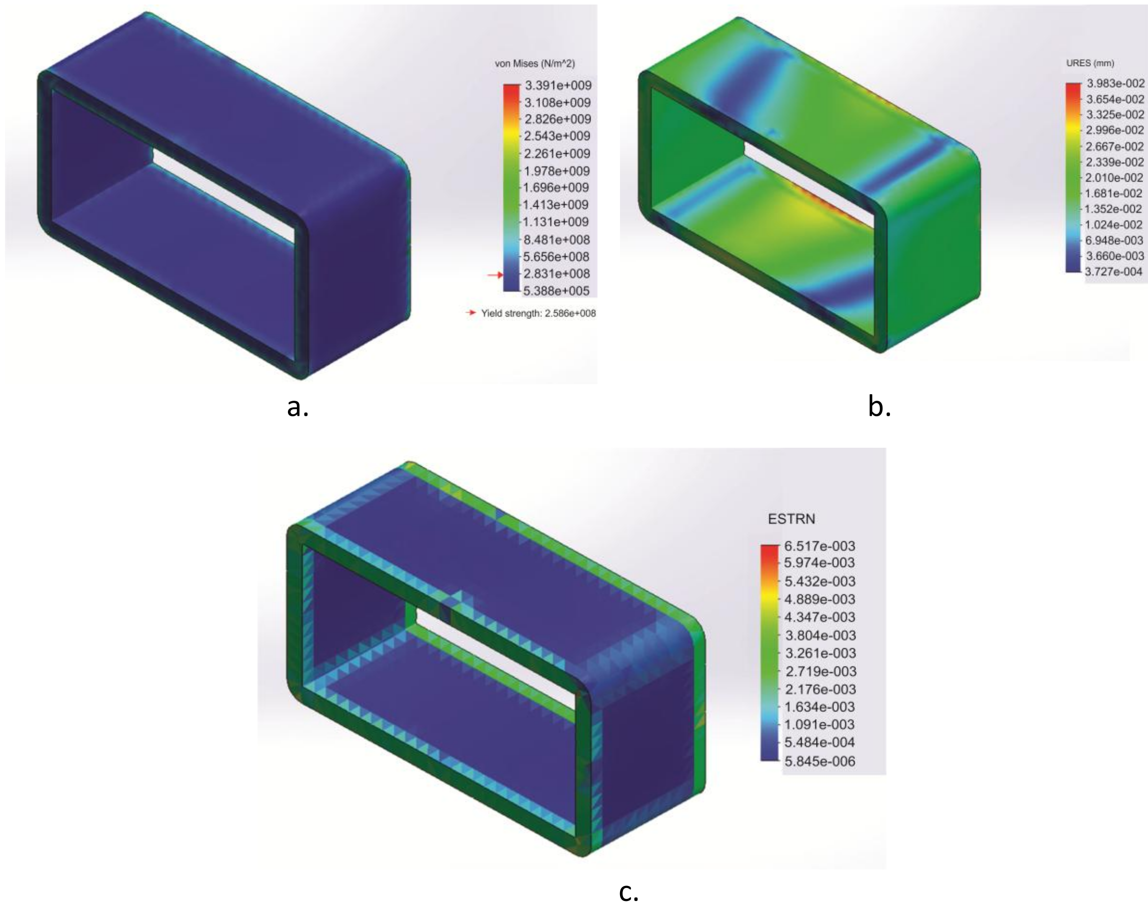


Figure 4.5.2.: The thermo- mechanical simulation results of the waveguide.

Some Cu mechanical parameters are shown in the Table 4.5.1.

Yield strength	2.58e+008 N/m^2
Tensile strength	3.94e+008 N/m^2
Elastic modulus	1.1e+011 N/m^2
Mass density	8900 kg/m^3
Thermal expansion coefficient	2.4e-005 /K
Table 4.5.1: Cu mechanical parameters.	

4.6. The thermoregulation system of the RF window

The vacuum RF window requires a thermoregulation system for an effective operation under the high power RF. The important part of thermoregulation system is corresponding circuit in the RF window.

The designed thermoregulation circuit scheme of the vacuum RF window is presented in the Figure 4.6.1.

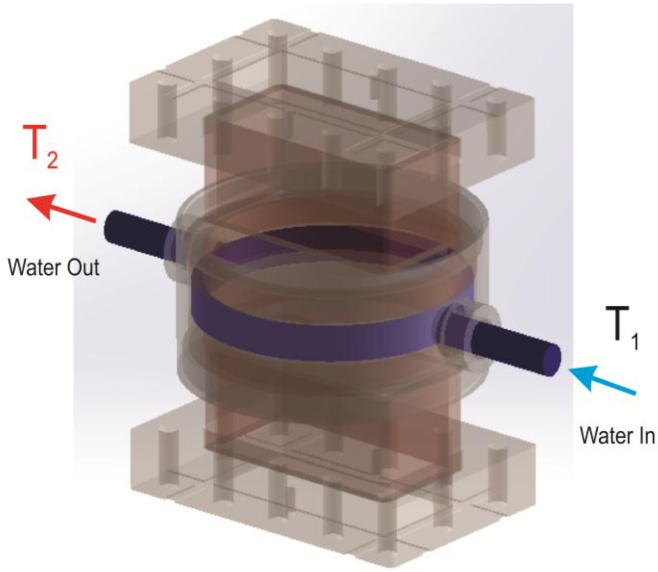


Figure 4.6.1.: The thermoregulation circuit scheme of the vacuum RF window.

There are many thermoregulation requirements for the vacuum RF window, these are high precision temperature and laminar flow for circulated liquid, fast and precise temperature control.

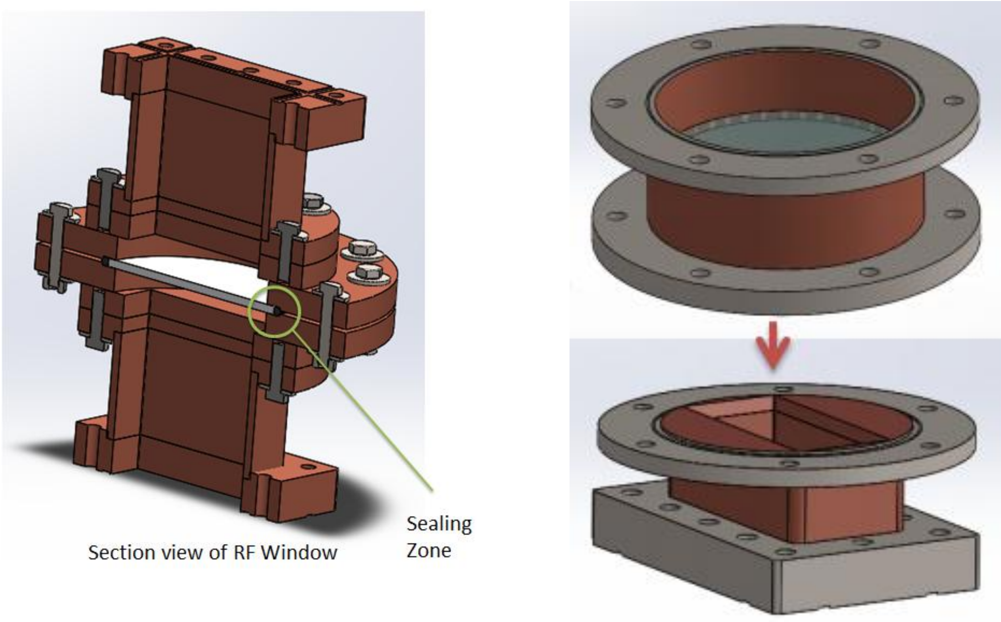
The deionized and distilled water have ideal properties for the RF window thermoregulation.

The deionized and distilled water are pure liquids with a high electrical resistance which are non-magnetic liquids.

4.7. The vacuum RF window test stand

The vacuum RF window test stand has been designed to test joint of different ceramic to metal and metal to metal for the vacuum RF windows under the vacuum, the temperature, the pressured gasses, the RF powers.

The main schematic view of the vacuum RF test stand is presented in the Figure 4.7.1.



a. b.

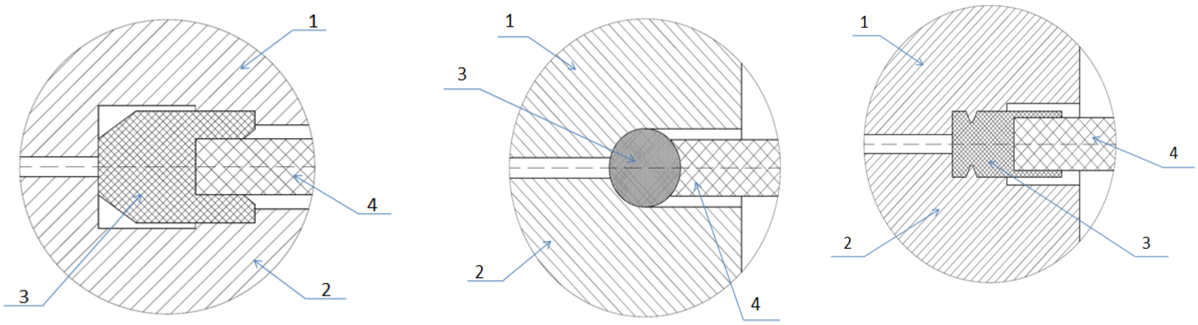
Figure 4.7.1. The vacuum RF window test stand

The vacuum RF window test stand has been designed to test the ceramic to metal sealing systems by removal sealing parts (Figure 4.7.1-a).

The vacuum RF window test stand has been designed to test the ceramic-metal brazing joint (Figure 4.7.1-b). The system has removal parts and can test different cylindrical ceramic-metal joints.

The special gasket systems have been developed for vacuum tight joints using special viton or teflon gaskets (Figure 4.7.2). These kinds of methods can achieve limited vacuum level.

The vacuum RF window using sealing (helicoflex) system has been developed and exists in accelerator technology [112].



a. b. c.

Figure 4.7.2.: The ceramic to metal sealing methods using viton or teflon.

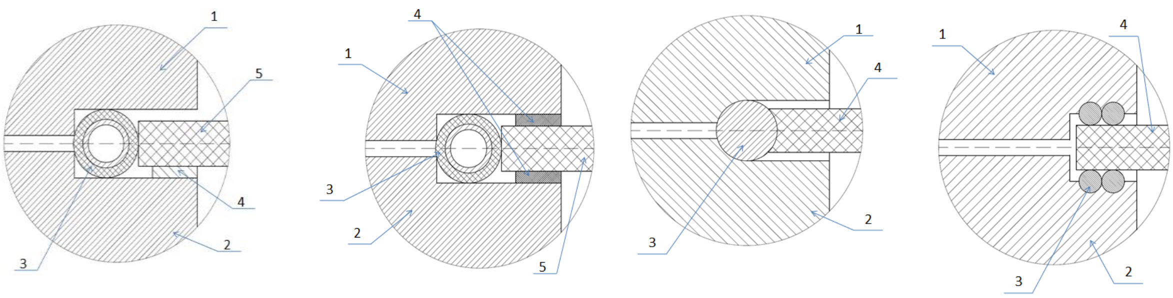
The system consists of the metal flanges (1 and 2), a sealing item (3) and a ceramic disc (4). Different shapes of the sealing items can be used for materials sealing (Figure 4.7.2-a,b,c).

The viton and teflon are vacuum materials which can be damaged under the electromagnetic waves and can be effectively used as a short time operation or under low level of electro-magnetic waves.

Viton is a fluoroelastomer polymer which works from -20°C to +200°C temperature. The outgassing level of the viton is approximately 1 x 10^{-8} (strongly depends on treatment type).

The sealing schemes have been developed using metal parts.

The developed sealing schemes of metal-ceramic joint are presented in the Figure 4.7.3. The ceramic to metal sealing methods can increase the vacuum tightness of joints.



a. b. c. d.

Figure 4.7.3.: The ceramic-metal sealing technology based on the combination of helicoflex and metals.

The developed systems are metal to non-metal combination (a and b) using only metal sealing parts (c and d) – Figure 4.7.3.

The components of developed sealing systems are 1- flange, 2-flange, 3-sealing part (metal or metal to non-metal combination), sealing metal parts (a and b), 5-ceramic (a and b), 4 ceramic (c and d).

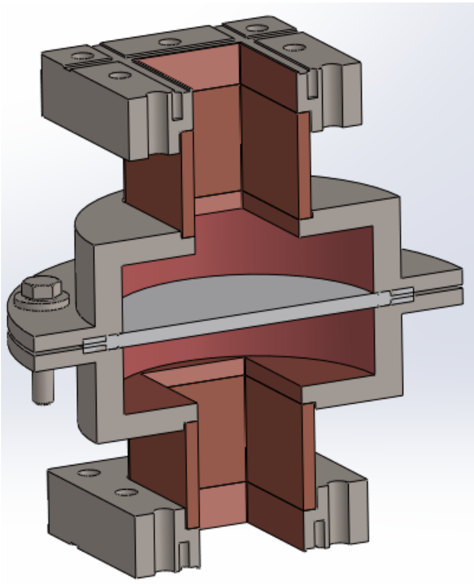


Figure 4.7.4: The RF test Stand.

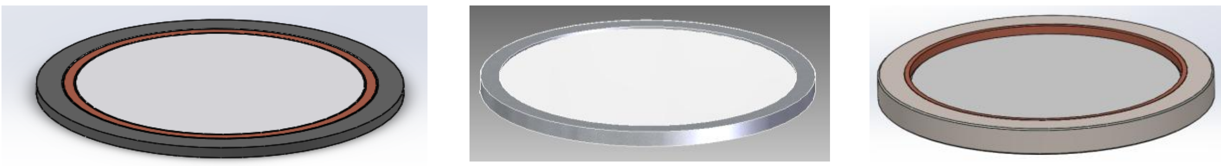
Special metal combination requires ceramic to metal sealing based on metals like aluminum, indium, indium and SS combination, aluminum and SS combination, copper and SS combination.

The test stand has been designed to test the developed metal to the ceramic sealing systems under the vacuum, temperature and high power RF conditions (Figure 4.7.4).

The ceramic-metal systems combinations have been designed for brazing processes. The developed ceramic-metal systems combinations are presented in the Figure 4.7.5.

The ceramic disc to metal combination systems are alumina to Cu with fixation of Mo ring (a), alumina to titanium (b) and aluminum to stainless steel ring (c).

The developed ceramic to metal schemes are preliminary sealing schemes and for the final realization additional research, design and experiments are necessary depending on the requirements.



a. b. c.

Figure 4.7.5: The ceramic disc to metal joints.

4.8. Development and investigation of the brazing process of copper to copper and copper to stainless steel for the RF windows

The metal to metal brazing technologies have been designed and experimented for the vacuum RF windows. The Cu to Cu and Cu to stainless steel items have been brazed in a vacuum furnace under the 10^{-5}Torr vacuum and 780^{0}C temperature conditions using Ag78-Cu28 solder. The brazed joints (a) and its metallurgical analysis (b, c, d - x200) are presented in the Figure 4.8.1.

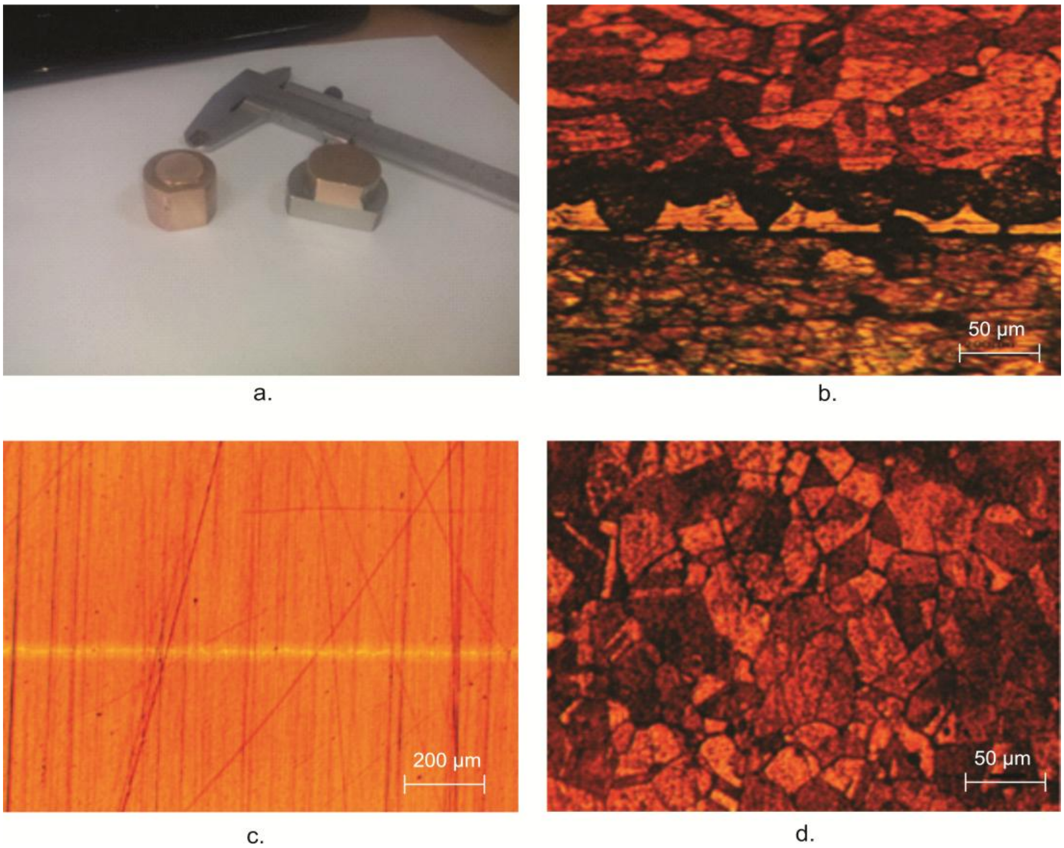


Figure 4.8.1: The Cu to Cu and Cu to SS joints.

The aqua regia was used for a chemical preparation of the machined and brazed joints for a consistent metallurgical analysis. The brazed zones of a stainless steel to Cu (b) and Cu to Cu (d) have high quality hermetic contact without interlayer emptiness. The Cu to Cu brazed zone is without chemical preparation (Figure 4.8.1- c).

The metallurgical investigation shows that high quality brazed zones have been achieved for Cu to Cu and Cu to stainless steel joints. As an experimental result the developed brazing technology can effectively be used for the vacuum RF windows.

4.9. The thermo-mechanical simulations of the RF windows during vacuum brazing

We have performed thermo-mechanical simulations for the designed vacuum RF windows under the 820^{0}C high brazing temperature conditions. The simulation results are shown in the Figure 4.9.1.

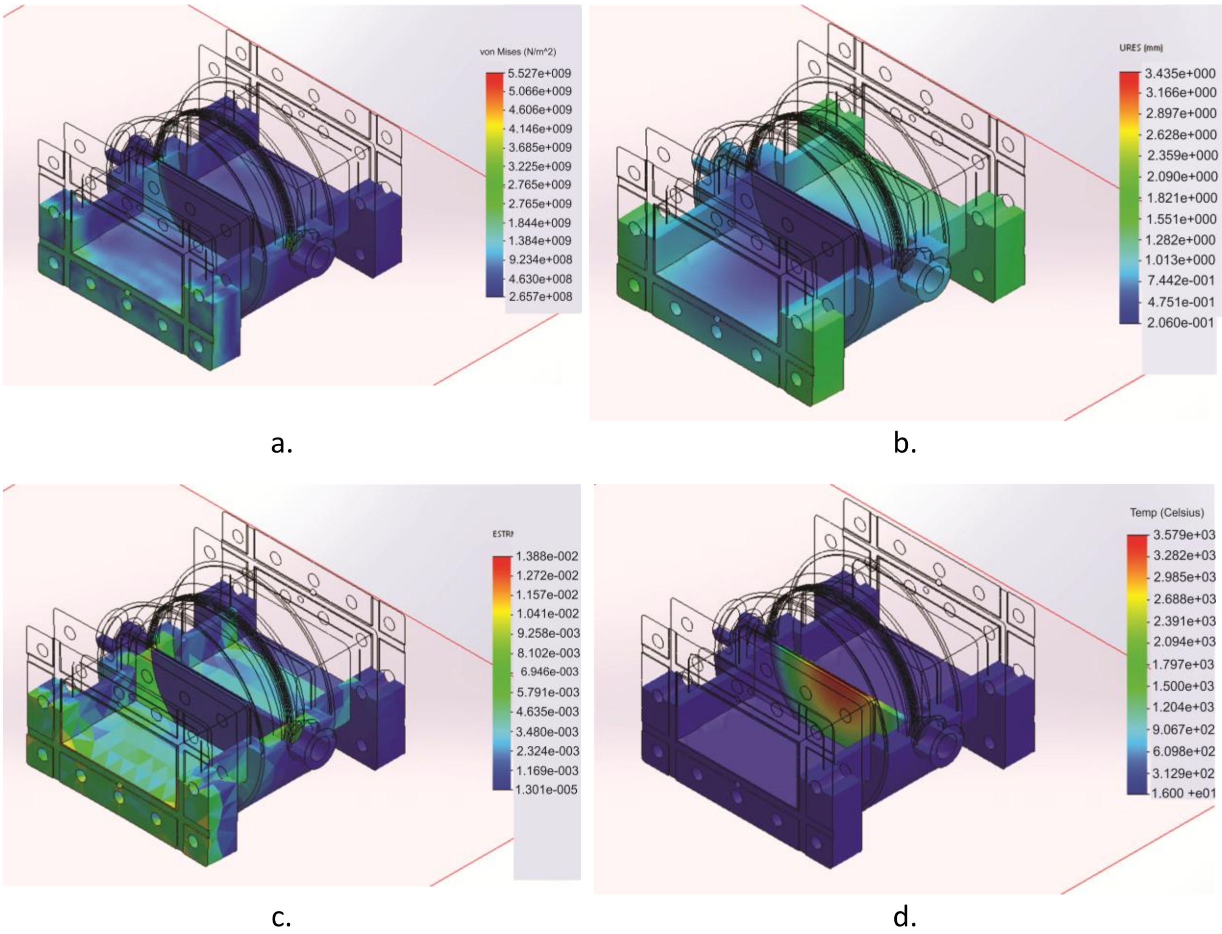


Figure 4.9.1: The thermo-mechanical simulation results of the RF window.

The simulation results of the stress (a), the displacement (b) and the strain (c) properties of the RF window under the 820^{0}C high brazing temperature conditions are presented in the Figure 4.9.1 - a, b, c. The maximum stress is 5.5 e+007 N/m^2 which is normal during an effective brazing process. The simulation result of the temperature gradient under 300W heat load is presented in the Figure 4.9.1 - d.

As a result of simulations we have found that the RF window structure has low stress, strain and displacement under 820^0C high brazing temperature conditions. The result of the thermo-mechanical simulations indicates the effective and reliable brazing specifications for the designed vacuum RF window.

4.10. The leak detection and the mass spectrometry

The leakage detection and the mass spectrometry analysis will be the next steps to test the brazed vacuum RF window. The leakage detection and the mass spectrometry tests are important to evaluate the quality of the joints.

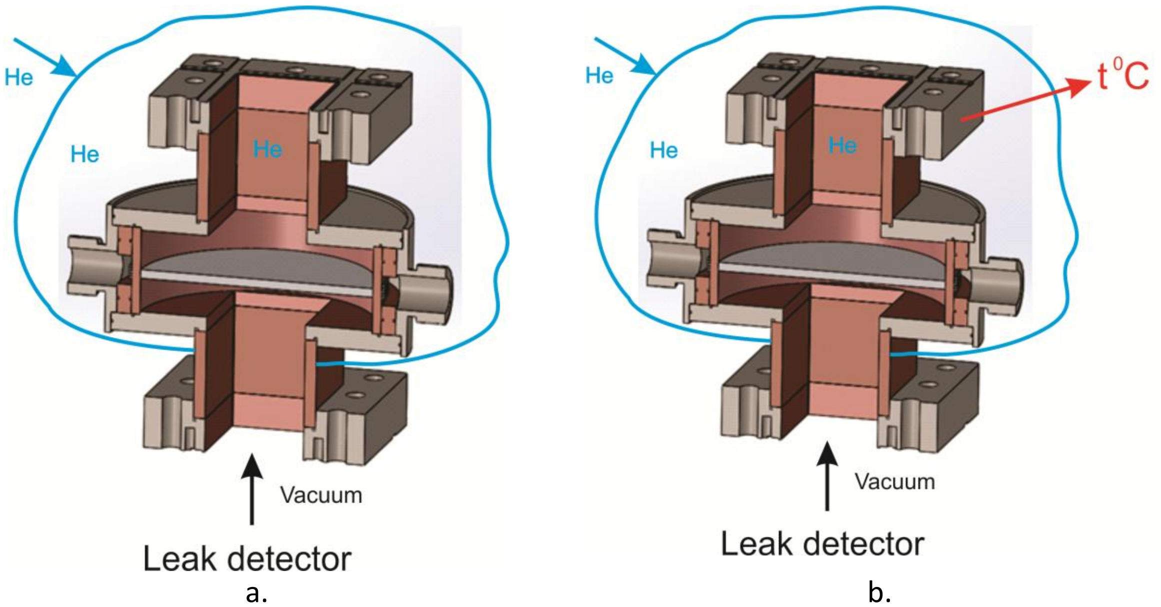


Figure 4.10.1: The helium leak detection methods.

There are many different leakage detection methods. The helium leakage detection method is a more sensitive and effective method for UHV components. The maximum leakage detection for helium leakage detectors is about 5×10^{-10} mbar l/s.

The leakage detection for the vacuum RF window must be implemented twice – a. Leakage detection to preliminarily evaluate the joint, b. Leakage detection under the high temperature conditions to evaluate the quality of the joint at more extreme working conditions (see Figure 4.10.1).

As a sensitive and precise device the RGAs (residual gas analyzers) are important instruments to evaluate the quality of brazed joints.

4.11. The Summary of the Chapter 4

- We have designed vacuum RF windows, including the material selection, the thermo-mechanical simulations, the development of the specific brazing technology, the evaluation of the fixation methods for materials, which was necessary to braze under high temperature conditions.
- We have designed a vacuum RF window test stand has been designed and assembled, which is used for testing the ceramic-metal joints under UHV, high temperature and RF conditions.
- The testing methods for the vacuum RF windows are specified, which includes leakage detection and RGA (residual gas analyzing) under room and high working temperatures.

Conclusions

1. We have developed the method of diffusion brazing, a new method for joining dissimilar ceramic and metallic items with complicated geometric shapes. For this we have used a pressure difference between the inner and the outer volumes of the joint system. The pressure in the inner volume of the ceramic-metal system is about 10^6 times lower than the pressure in the outer volume.
2. We have developed the method of diffusion bonding, a new method for joining cylindrically-shaped ceramic and metal items. The assembled items should be heated up by the applied electrical current using the fixed metal wire. The inner ceramic material and the fixed metallic wire have similar coefficients of thermal expansion which are lower than the ones for the outer cylindrical metals.
3. The thermoregulation systems for a precise operation of the vacuum electromagnetic equipment (Klystron, RF gun) of AREAL linear accelerator have been designed and fabricated. The thermoregulation system of klystron provides +/-0.5^{0}C temperature accuracy. The thermoregulation system of the RF gun is a precise and fast system which provides +/-0.1^{0}C temperature accuracy.
4. We have designed and fabricated the Ultra High Vacuum (UHV) test stand which is being used for testing and investigating separate accelerator components.
5. The commissioning temperature range of the vacuum tight ceramic-metal joints has been determined by calculations and experimental results. The experiments have been carried out under 130^{0}C temperature and $7{\cdot}10^{-9}$ Torr vacuum conditions.
6. We have designed a vacuum RF (Radio Frequency) window. The stress and strain properties of this RF window have been determined by numerical modeling techniques, assuming a diffusion brazing temperature.

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