Highly Leak-Tight Ceramic-Metal Assembly for a Novel, Three-Dimensional Imaging X-Ray Process

Alumina Systems/DE cooperates since more than four years with Adaptix/GB to develop a new 3D FPS (Flat-Panel X-Ray Source) which offers 3D-imaging for a similar radiation dose and cost to traditional 2D X-ray. The cooperation in the last years enhanced technology on both sides and today we can say that this product can be a game changer on the X-ray market. In the following chapter, some of the design and process decisions, as well as the resulting consequences, which led to the development of this potentially groundbreaking product, are shown. The development process used partly, but not exclusively, the approach of "integrative design with ceramics" propagated by Prof. Maier.

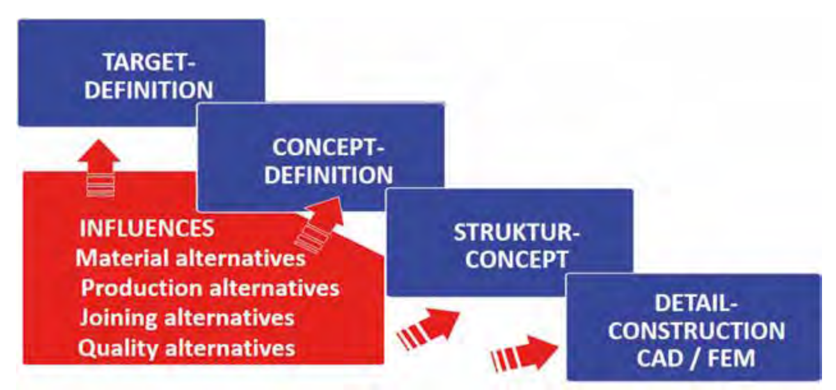

Fig. 1
Integrative design with ceramics

The process started with an inquiry about the producibility of a vacuum-leak-tight ceramic metal joint, having similarities with thyristor housings, Alumina Systems is producing since more than 30 years using brazing technology to join copper to alumina ceramics, creating vacuum-tight joints. These systems are used in HVDC-Systems (High Voltage Direct Current) to transmit energy in point-to point connections in the range of 5–12 GWh. Applications are dams, or high-power wind mills, where a high amount of energy has to be drained. The idea was a vacuum enclosure with partial pressure lower than $1 \cdot 10^{-8}$ mbar on the inside of the enclosure, the use of a ceramic with high electric insulation value (preferably alumina) with brazed stainless steel plates on the ceramic upper and lower surface. The whole component in a rectangular shape and an operating temperature lower than 150 °C with the ability to maintain the vacuum for a long period of time (approx 3–5 years). At this stage of the product development the basic functionality of the product was developed and the basic requirements for the future component were set, but not finally verified yet, so there was a big design-room available for the solution. The main goal was to achieve an affordable, rugged and reliable solution to use the vacuum enclosure for the generation of X-rays for a new generation of a three-dimensional imaging X-ray process.

Keywords
X-ray, ceramic-metal-joints,
ceramic brazing, ceramic joining

This required the enclosure to be finally sealed at the customers facility in high-clean conditions. The following requirements have been defined:

- Metallic disks made from aluminium (instead of stainless steel),
- The shape should be round instead of rectangular to reduce joining stresses,

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Fig. 2
Ceramic thyristor housing

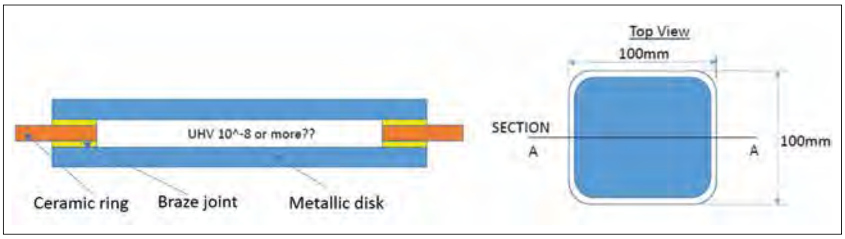

Fig. 3
Comparison of a brazed thyristor housing with the first product idea

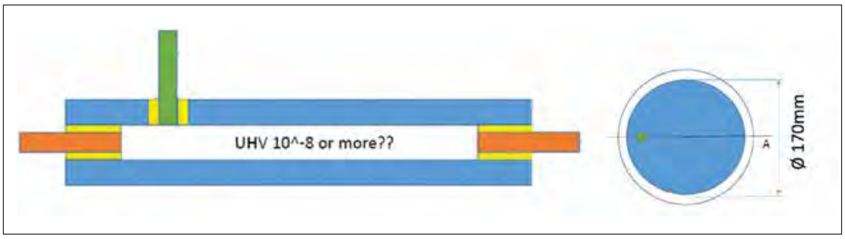

Fig. 4
Starting geometry consisting of a ceramic ring, two aluminium plates and a copper pinch-off tube

- The cathode plate (bottom metallic plate) should be joined to the alumina ring with a helium leakage rate lower than $1\cdot10^{-9}$ mbar l/s,
- The X-ray source (structured silicon wafer) will be joined to the cathode plate in a yet to be defined process,
- The anode plate (top metallic plate) will be joined at Adaptix with flux-free solder. So, the top surface of the ceramic should be prepared for the final soldering process.
- The joints need to withstand a bake-out temperature of the whole component not higher than 180 °C in ultra-high vacuum.
- A copper pinch-off tube (POT) is to be inserted into the anode plate.
- Material have to be suitable for ultra-high vacuum applications.

From these requirements the starting geometry resulted as shown above.

Since the use of aluminium was preferred as a material for the anode plate, a suitable joining technology has to be found or developed, since the standard passive brazing using a silver-copper eutectic braze was not suitable for brazing aluminium because of the high brazing temperature of 780 °C. Using 88Al12Si was rejected since high differences in the thermal expansion of aluminium and alumina were expected.

Since the maximum temperature of 180 °C was low, it was decided to use solders to create the braze joints since the melting temperature of >240 °C and the used materials in the solder materials met the requirements of being suitable for ultra-high-vacuum applications.

Since wetting of solders even on metallized ceramics is not sufficient and a flux-less process was required, ultrasonic soldering was investigated as a potential production technology. Although optically good joints between the alumina ring and a massive aluminium plate could be achieved, the joints could not meet the requirements of the helium leakage rate below $1\cdot10^{-9}$ mbar l/s. The best helium leakage rate that could be achieved was $1\cdot10^{-6}$ mbar l/s.

Since the results after several design adjustments were not satisfying, a redesign was proposed, which was mainly based on known technologies to be able to reliably produce cathode housings that will meet the requirements concerning helium leakage rate and used materials.

It was decided to produce the cathode housing analogous to the already produced thyristor housings using a metallized alumina ceramic with brazed copper membranes and a copper contact piece as the cathode plate. Additionally, a way had to be found to connect the silicon wafer

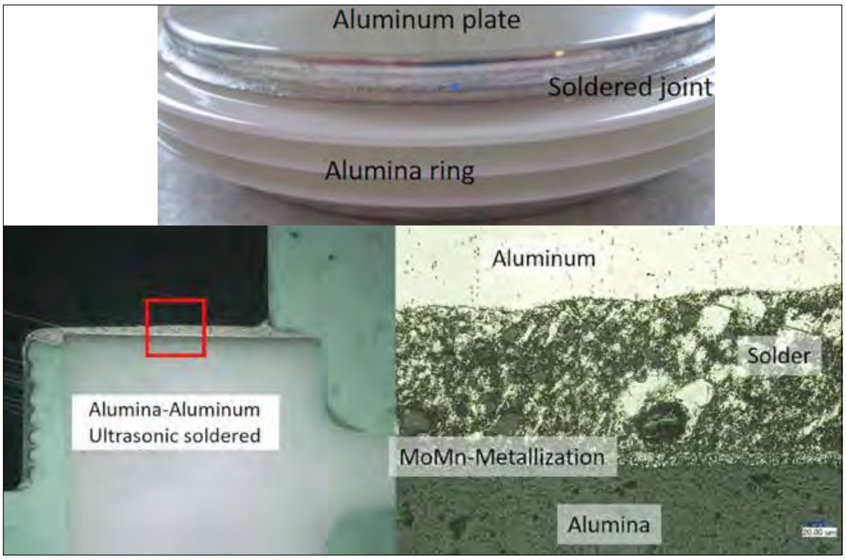

Fig. 5
Ultrasonic soldered test-part

Fig. 6
First design iteration with change of production technology

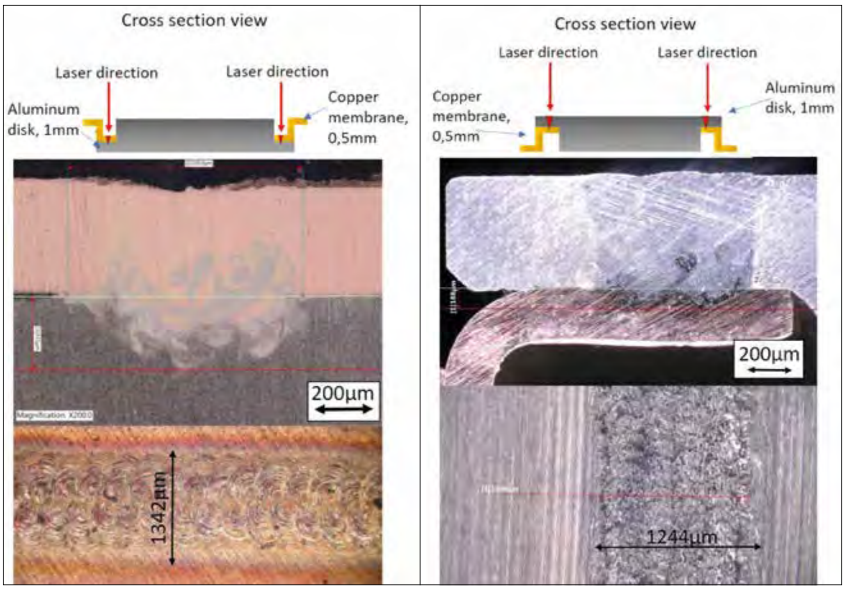

Fig. 7
Laser welded aluminium-copper joints

mechanically and electrically to the copper plate. To be able to wet the silicon wafer with a solder, the back of the wafer was gold plated.

Another critical, not yet solved issue was the joint between the aluminium anode plate and the copper membrane brazed to the ceramic. For this joint two parallel approaches have been investigated:

- A soldering joint using a standard low temperature solder,
- A weld-joint using laser brazing.

Since it was reported that mechanically stable weld-joints between copper and aluminium could be achieved, this was the preferred investigation path. Welding tests with different combinations of copper and aluminium have been conducted in which the following influencing parameters were considered:

- Laser direction and coupling (into copper or aluminium),
- Modification of copper surface by nickel plating.

Results of some trials are shown above. In the trials optical appealing and mechanical stable joints could be produced with both coupling strategies. Nevertheless, the requirements concerning leak tightness could not be met.

Some joints could be produced that showed helium leakage rates of $1\cdot10^{-7}$ mbar l/s, but these values could not be reproduced reliably.

It is assumed that the leakage paths are created by the formation of brittle copper-aluminium eutectic phases that emerge in the intermixing regions of both materials in the weld joint showed above in the micrographs. As a final sealing-step technology this approach was not expedient.

The other approach using a solder (flux-less in the last sealing step) incorporated the following process steps:

- Production of the cathode housing,
- Prewetting of the anode copper membrane with solder,
- Prewetting of the aluminium anode plate,
- Reflow-soldering step in vacuum.

In preliminary trials the validity of this approach could be proven. Joints that showed helium leakage rates $<1\cdot10^{-9}$ mbar l/s could be created with the proposed procedure. The main problem with this approach was the reliable prewetting with solder of the copper and aluminium components. For the prewetting of the copper membranes flux containing solder pastes and special designed presoldering forms had to be used, which put high demands on the following washing process to clean the part for the final assembly under high vacuum conditions.

While the prewetting process for the copper membrane of the cathode housing was quite straight forward and reliable, the prewetting of aluminium was challenging, since aluminium is not wetted by solders, even solder pastes containing fluxes.

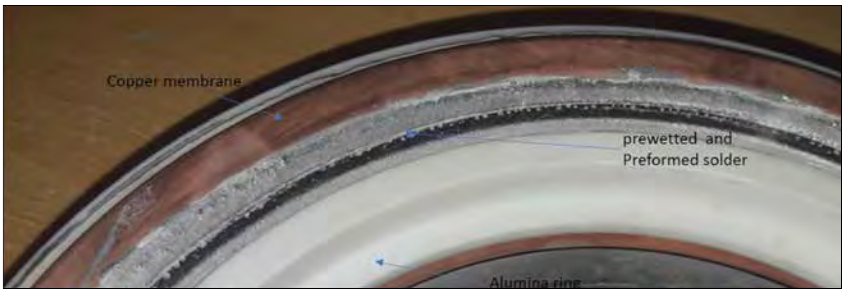

Fig. 8
Brazed copper membrane with prewetted and preformed solder

Fig. 9
Aluminium prewetted with active solder before and after reflow soldering

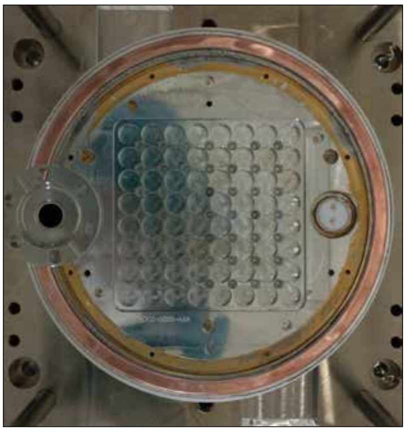

Fig. 10
Assembled housing

Thus the already tested ultrasonic soldering process in combination with active solders containing titanium and chromium has been used to apply a base solder layer on the aluminium. Since the results on pure aluminium did not show satisfying results concerning the reliable wetting, different coatings were tested to improve the wetting behaviour of the solder. The required reliability for a stable production process could nevertheless not be achieved for the reflow sealing process, since unexpected leakage of the soldered joint occurred several times. The cause of the leaks was found to be always on the aluminium side of the solder-joint. When analysing the failed joints by reheating the joined assembly to remove the anode plate it was found that the reflowed solder did partially not wet the aluminium anymore. These regions also could not be wetted with ultrasonic solder anymore.

Nevertheless, first successful high voltage tests up to 66 kV could be achieved with parts made by this production route. In these tests it showed that higher bake-out temperatures were needed to completely remove residues on the component surfaces. Therefore, joints that could exhibit higher bake-out temperatures had to be used. This was one of the main reasons, the use of aluminium for the anode plate had to be changed to titanium.

For the above reasons, a change of design was implemented, with a change of material and joining process, with the requirement now being a solder-free titanium/ceramic/copper assembly. The joining process of both copper membranes using a vacuum laser welding process was investigated separately.

- Classic laser welding process using additional copper wire;
- A combined laser welding/laser brazing process in which the membranes are welded first and in a second step are over brazed with silver-copper-eutectic braze.

The investigation showed a high reliability of both joints. It was found, that some test parts using the copper-copper laser-weld process without the silver copper eutectic

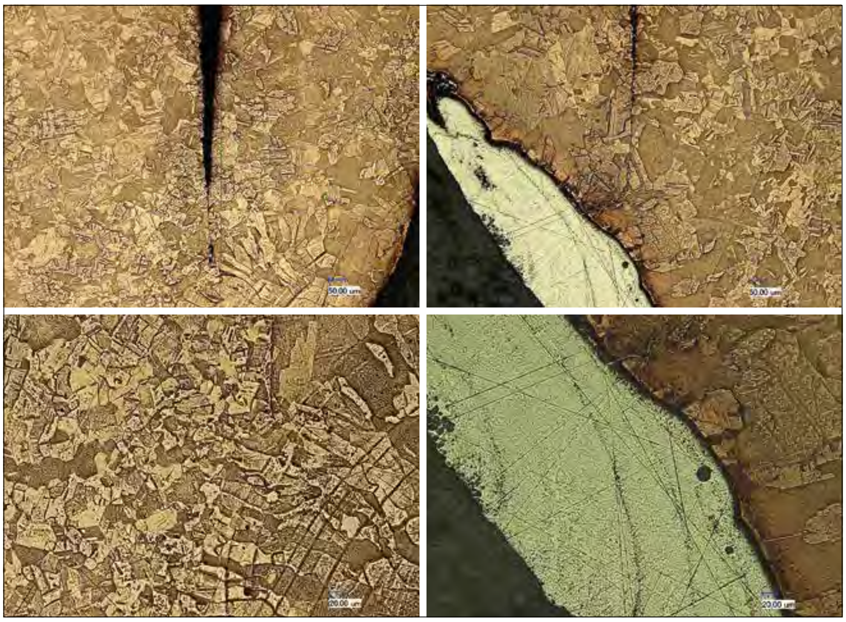

Fig. 11
Copper-copper laser-weld-joint (l.), and copper-copper laser-weld-joint with additional AgCu-eutectic braze (r.)

Product Details

Acquisition time: <5 s
Image reconstruction time: <20 s
Weight of mini C-arm: <20 kg
Detector area: 15 cm × 11 cm (Version 1)

Options: Vertical mounting to allow to move easily between standing foot to arm or standing shoulder acquisition

Fig. 12
Product design study

braze had some minor leaks, caused by microscopic cracks in the joint resulting in a helium leak rate of $1\cdot10^{-8}$ mbar l/s. These minor leaks have not been found using the additional AgCu braze. As can be seen in the above figure, the braze can fill minor surface cracks in the weld-joint resulting in an overall more reliable process and consistent helium leakage rate smaller than $1\cdot10^{-9}$ mbar l/s. During the development process for the joining technology, further minor and mayor modifications of the design had to be adapted:

- Attachment of the silicon wafer,
- Design-changes of the inner ceramic geometry to improve electron scattering and high voltage stability.

With implementation of the above-mentioned points Adaptix Imaging Ltd. was able to build running prototypes of the system that could be used outside of a laboratory environment.

Fig. 13
Human metarcarpal

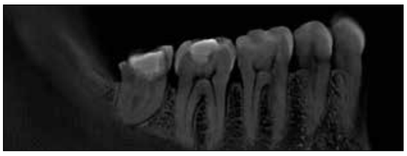

Fig. 14
Cut through human teeth row with fillings

Application can be seen in:

- Orthopedics,
- Dentistry,
- Other applications in development.

Alumina Systems supplies the vacuum enclosure, which is delivered as a parted casing. Adaptix applies the chip and welds the part under UHV (Ultra High Vacuum). The casing consists of a Metal-to Ceramic brazed component, where the different brazing processes are consequently arranged to the descending brazing temperatures.

Adaptix's FPS uses a square array of emitters instead of just a line. It has the potential to enable lower-cost, smaller footprint, higher performance 3D imaging (tomosynthesis) devices that are compact enough to be employed at the patient's bedside. The FPS is composed of an array of cold cathode field emitters that can produce X-ray energies in a range relevant for medical imaging: 20–120 keV. The array generates a large number of overlapping X-ray conelets, and a raster system allows for each X-ray emitter to be fired individually or in clusters. Control of the emission process is achieved through electromagnets, avoiding the common problem of high-voltage switching. The use of a square array for tomosynthesis enables the source to be much closer to the patient than standard CXR stand-off distances, which greatly reduces the required input power.

This innovative approach is complemented by application of novel image reconstruction techniques producing a slice-by-slice reconstruction which enables extremely quick partial analysis and adjustment of slice thickness over regions of interest. The approach uses backprojection together with a ramp-filter, and is substantially less memory intensive than techniques that must reconstruct the volume as a whole.

In addition, noise and artifact reduction techniques and the ability to reconstruct slices in super-resolution improve the reconstruction quality, whilst computational optimization ensures that the method is fast.

Applications

Orthopedics

- The Adaptix desktop 3D ortho imaging system has a cost and dose similar to existing 2D X-ray systems;
- Point-of-Care, low-cost, low-dose 3D diagnostic imaging of extremities;
- Accelerated workflow;
- Enhanced diagnostic confidence;
- Reduced need to move or refer patents

Fig. 15
Study of chest scanner

- Ability to do weight bearing foot imaging;
- Compact device: mini C-arm weight <20 kg.

Dentistry

The Adaptix dental imaging device offers low-dose, high-resolution, intraoral 3D imaging at the chair-side.

- Improved identification and characterisation of caries lesions in 3D;
- Easier communication of the need for procedures to patients;
- Better assess unerupted teeth;
- Better assess impacted wisdom teeth;
- Provide pre-operative root-canal imaging to better identify multiple root canals in a single tooth prior to surgery;
- Potential for intra-operative root-canal imaging to check the placement of files and gutta-percha filler.

Chest imaging

A future version of the device will offer truly mobile 3D chest imaging at the bedside for a cost and dose similar to existing 2D X-ray systems:

- Better visualisation than 2D X-ray of common conditions such as pulmonary edema, pneumothorax/hemothorax and more confident localisation of lines and tubes;
- Low-dose offering the chance for more frequent follow-up 3D imaging;
- The ability to acquire a 3D image without moving the patient from their bed;
- Reducing the need to transfer patients within the hospital to access 3D imaging – lower cost, less risky for the patient, less risk of infecting other patients and no need for lengthy cleaning of a scanner after imaging an infectious patient.