THE XRMON-GF MICROGRAVITY EXPERIMENT MODULE

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ABSTRACT

To provide an opportunity to use X-ray diagnostics in microgravity solidification experiments, ESA initiated a hardware development project. The objective was the "Design, manufacturing and testing of a fully functional X-ray diagnostics breadboard suitable for the *in situ* investigation of directional solidification in alloy melts up to 1100K". The **XRMON-GF** module is the first sounding rocket module developed implementing this technology. The module is designed with the aim of being possible to re-use for future experiments within the XRMON MAP programme.

A Bridgman furnace with two heating zones independently adjustable in temperature to impose a longitudinal thermal gradient to the sample has been developed. The experiment will be conducted in pressurised environment. This Gradient Furnace enables directional solidification of samples with dimensions up to 10x50x0.2 mm with thermal gradients within the range of 1-10 K/mm. Special care in the choice of furnace and crucible materials has been taken to provide good X-ray transmission without compromising the thermal properties. A motorised positioning device has been implemented to enable sample solidification by pulling, as well as sample positioning in the field of view of the Xray diagnostic.

The high resolution X-ray radiography diagnostic system consists of a microfocus X-ray source and a digital X-ray camera using a novel scintillator technique developed within the ESA "X-ray Diagnostics for Space" GSTP study. There will be on-board storage of uncompressed images, as well as provision of real-time digital image down-link to the Science Team at Esrange Space Center.

1. XRMON PROJECT

Structural material properties are related to their solidification microstructures which can be columnar (oriented properties) or equiaxed (isotropic properties). The control of the columnar-to-equiaxed transition is thus crucial in engineering and is still a debated subject [1]. On Earth, natural convection in the melt is the major source of various disturbing effects [2,3]. Solidification under microgravity is an efficient way to eliminate buoyancy and convection to provide benchmark data for the validation of models and numerical simulations [4,5].

In situ and real-time imaging of the metallic alloy solidification can be achieved by applying synchrotron X-ray techniques, in particular X-ray radiography [6,7]. In this technique, the contrast in the recorded image is due to local changes in the amplitude and/or phase of the X-ray beam transmitted through the sample. A (monochromatic) X-ray beam illuminates the sample and a 2D-detector (photographic film or CCD camera) is placed close to the sample to record the transmitted beam. In alloy systems, contrast mainly results from segregation of the chemical species and is generally weak and therefore difficult to reveal with conventional X-ray sources.

The main objective of the ESA - MAP research project entitled XRMON is to conceive and perform *in situ* X-ray radiography experiments on metallurgical processes in microgravity environment. XRMON has been selected to be flown on the MASER 12 sounding rocket mission, scheduled in autumn 2011. This paper reports on the technical description of the dedicated novel experimental set-up developed by SSC (Swedish Space Corporation).

2. EXPERIMENT REQUIREMENTS

2.1. Requirements on sample melting and solidification

In order to melt and solidify the sample in microgravity, the furnace will allow a heating ramp with a speed of 2 K/s. To provide a reproducible result, temperature measurement must be made as close as possible to the sample and with a high accuracy and a known deviation. The temperature gradient over the sample must be uniform and independent of gravity. The temperature

Proc. '20th ESA Symposium on European Rocket and Balloon Programmes and Related Research'
Hyère, France, 22–26 May 2011 (ESA SP-700, October 2011)

across the width of the sample must be homogenous and the cooling effect from the borders minimised.

It will be possible to induce solidification by two different methods. The first method consists of pulling the sample towards the cold part of the furnace and thus sample movement must be provided. The second procedure is the *power-down* method, with displacement of neither the sample nor the furnace. In this method, solidification is triggered by applying either a cooling rate only on the hot zone of the furnace while maintaining the cold zone temperature constant or the same cooling rate on both heater elements.

2.2. Requirements on X-ray diagnostic

Al-Cu alloys will be used in the frame of this project. The X-ray diagnostic device shall have an energy range around 17 keV, to take advantage of the difference in transmission between copper and aluminium. To get optimal image quality the materials in the X-ray path must be minimised and selected to have low attenuation. An image frame rate of, at least, 3 frames/s is required to follow the dynamics of the solidification microstructure formation.
Downlink of compressed image is necessary in order to follow the experiment progress and be able to fine-tune heaters temperature during flight, if necessary.

2.3. Requirements for future experiments

Since the module is intended for future re-use with other experiments, some additional requirements must also be added although they are not crucial for the first flight.
In order to utilise the radiation from a microfocus X-ray tube optimally a transmission type X-ray tube shall be used. The distance between the focus point and the sample shall be minimised and preferably ≤ 5 mm (Fig.1).

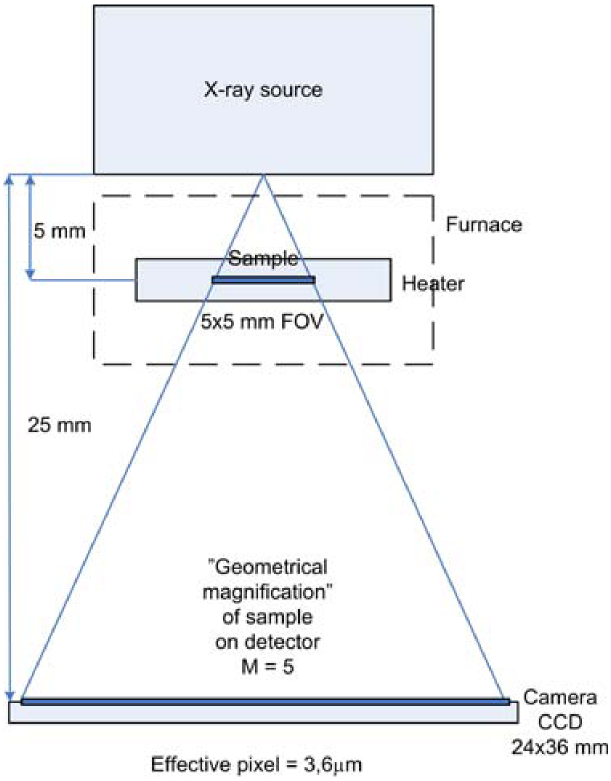

Figure 1. X-ray system geometry

3. EXPERIMENT SYSTEM

3.1 Sample-crucible assembly

The sample is made of Al-20wt%Cu, with dimensions of 5x50 mm and 180 µm thick. In order to contain the melted sample, it is enclosed in a crucible. The crucible outer size is 15x80 mm, and made of two 150 µm thick quartz glass sheets. The glass sheets are welded along the long edges and left open in the short ends.
To reduce the risk of crucible break due to the differences in thermal expansion between the metal sample and the glass, the sample is covered by a protective layer of boron nitride (BN), approx. 20 µm thick. The BN coating is also required to prevent chemical reaction between the Al-Cu sample and the glass plates. In addition, it is transparent to X-rays in the range of energy of our interest. To provide connection to the motor arm a "grip" of stainless steel is glued on the crucible bottom end (Fig.2).
An alternative solution has also been suggested for the crucible using "glassy carbon", a special form of graphite. Decision on this will be taken later.

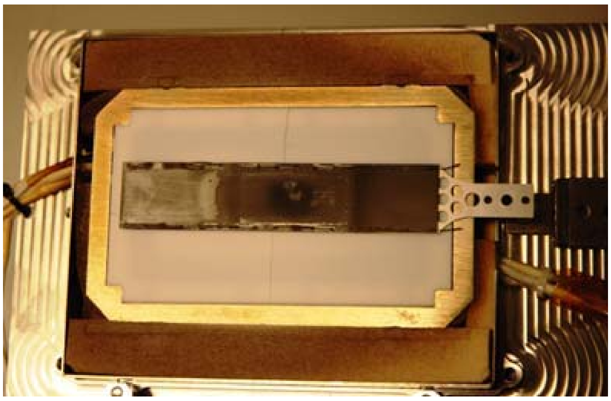

Figure 2. Crucible placed on top of furnace, motor Arm on the right

3.2 Gradient furnace

The gradient furnace is of Bridgman type and has two identical heaters for the “hot” and “cold” zones (Fig.3). In order to provide the same thermal behaviour in microgravity environment as on 1g these are designed so that the crucible is enclosed inside the heater body, having contact from both sides. The heater wire is applied in a coil-like fashion, encompassing both sides of the heater. Thus the upper and lower part of each heater element will get the same temperature.

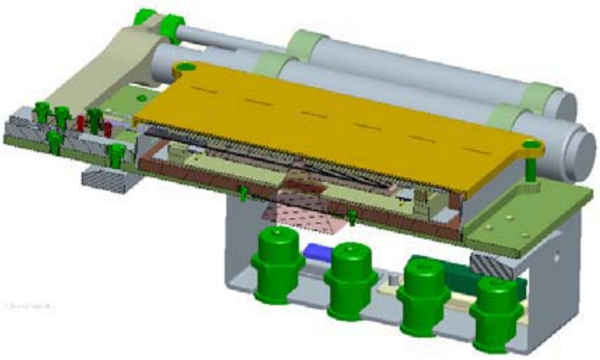

Figure 3. Cross section of furnace, X-ray beam in middle, motor on far side

It is important that the two heaters have no contact with each other in order to get all heat transfer through the sample. The heater gap should have a “hole” for X-ray beam (Fig.4), but at the same time it is important to not get cooling from the sides.

The heaters are regulated independently using a PID-regulator implemented in software. Two thermocouples in each heater measure the temperature close to the crucible and serve as input for the temperature regulation.

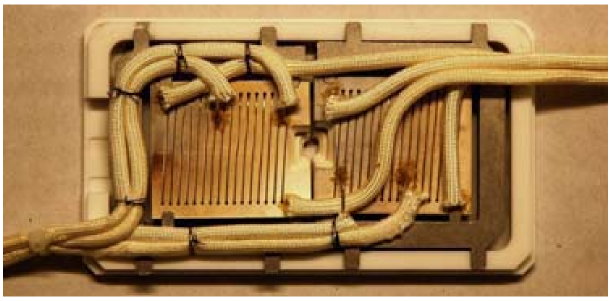

Figure 4. Heater bodies in supporting frame

The requirement of 5 mm distance between the X-ray tube exit window and the sample greatly reduces the amount of isolation possible to use. Isolation is however crucial to achieve the thermal homogeneity needed for the experiment. Here it is important to get a compromise between the two requirements.

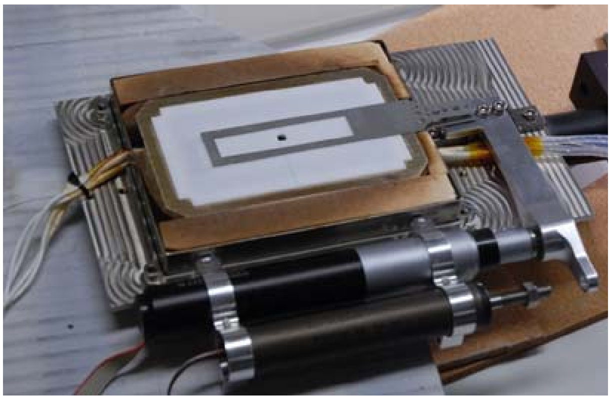

Figure 5. Assembled furnace, crucible frame placed on top to show sample placement

Solidification of the sample can either be made by regulating the temperatures of the heater elements or by pulling the sample in the furnace, thus moving the solidification front along the sample (*power-down* method). The motorised movement can also be used to position the sample in the field of view (Fig.5).

3.3 Imaging system

The imaging system is made of three parts: The X-ray tube, the camera and the Digital Video System.

3.3.1. X-ray tube

A microfocus X-ray tube with 5 μm focal spot or better should be used in order to meet the resolution requirement. To be able to achieve the requirement of ≤ 5 mm focus-sample distance, a transmission type X-ray tube is needed since these have the focus point in the exit window. Conventional X-ray tubes typically have ≥ 5 mm distance focus point-exit window.
A compact oil-free version of an X-ray tube of this type has recently been developed by Viscom AG, Germany in cooperation with DLR (*Deutsches Zentrum für Luft- und Raumfahrt e.V.)*. This X-ray tube (Fig.6) is intended for usage on the International Space Station but it is also possible for use in sounding rocket projects. This system will have its first flight on Maser 12.

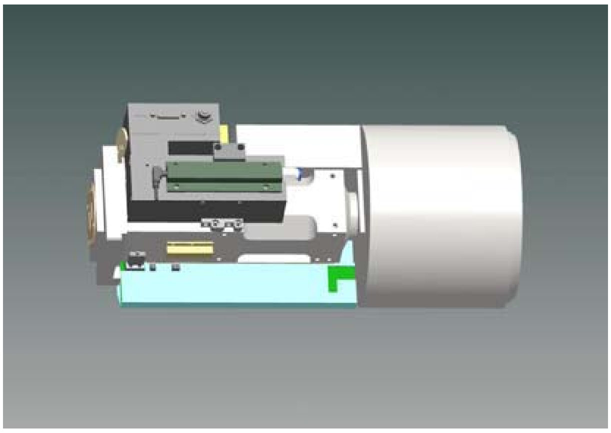

Figure 6. X-ray tube assembly

3.3.2 Camera

In the scope of the ESA GSTP study "Xray Diagnostics for Space" a camera system was developed that fulfils the requirements of the project (Fig.7). The camera system is made of a digital camera with a 24x36 mm CCD-sensor adapted for X-ray usage by the integration of a 50 mm thick fibre optical plate that protects the sensor from radiation. A scintillator plate placed in front of the optical fibre converts X-ray radiation to visible spectrum light. The used scintillator is a "structured scintillator", based on a new technique with channels etched in silicon and filled with scintillating material, acting as wave guides. This new development is patented by Scint-X AB, and was refined in the scope of the GSTP study. During this project further improvements to the methods for scintillator production and integration have been made, further improving the homogeneity and luminescence of the camera image.

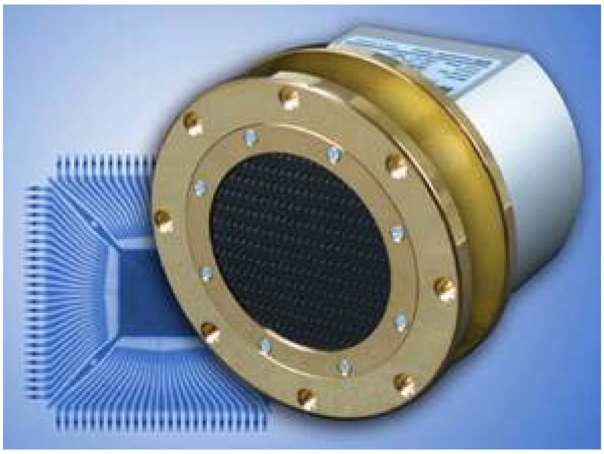

Figure 7. X-ray camera

3.3.3 Digital Video System

The Digital Video System interfaces the camera and provides camera control, image storage and downlink. The system selected is a H2VMU from Techno System Developments Italy. This unit can store uncompressed images (Fig.8) on-board with a frame rate up to 6 frames/s, with real time gain compensation from a reference image implemented in the hardware. Compressed images will be down-linked with a frame rate of 0.5 frame/s during flight.

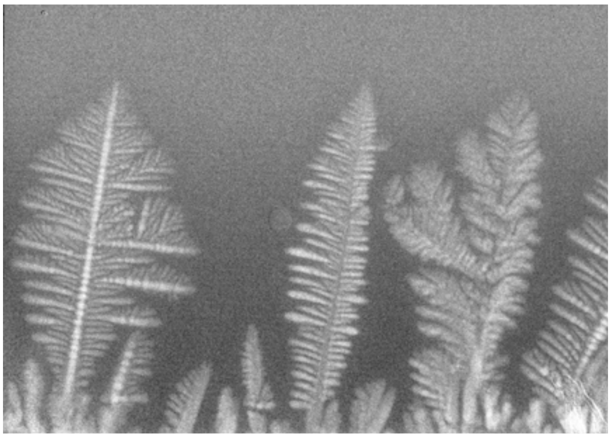

Figure 8. X-ray image of a growing columnar structure of Al - 10wt% Cu (R_H = 12K/min; R_C = 0; G ≈ 4 K/mm) Image width=4.5 mm.

4. MODULE MECHANICS

XRMON-GFis a 115 cm tall and 120 kg heavy Module (Fig.9).

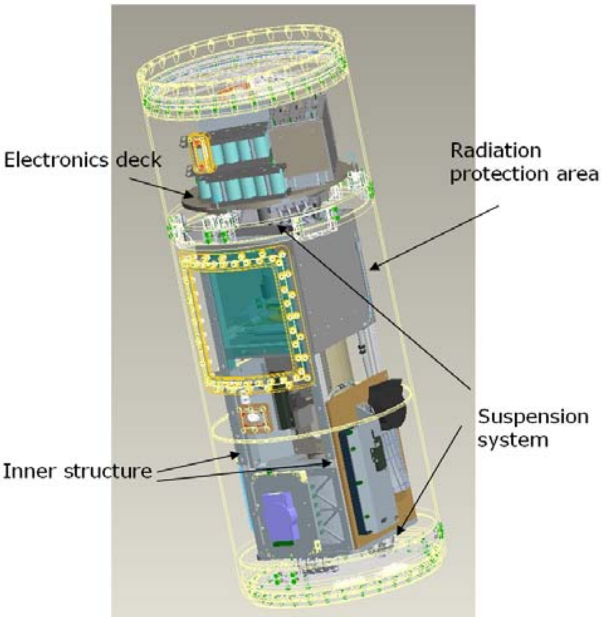

Figure 9. Module assembly, outer structure indicated

4.1 Inner structure

To provide a stress-free environment for the experiment system during take-off it is mounted in an inner structure suspended on a tuned damper system. This method was tested in the XRMON foam experiment flown on MASER 11 and proven successful. The parameters have been adjusted for the longer and heavier system used in XRMON-GF. The inner structure also serves as a support for mounting experiment electronics and for the X-ray shielded compartment.

4.2 Electronics deck

The electronics system, apart from the two experiment electronics boards which are mounted on the inner structure, is mounted on the electronics deck placed on separate dampers above the inner structure (Fig.10). On this deck the Electronics cabinet is placed containing the Experiment Control Computer which provides the experiment control sequence, on board data saving and in-flight communication. A separate computer board provides control for the X-ray tube and a Housekeeping Board that conditions and monitors the module voltage and currents and other housekeeping data. The Digital Video System cabinet and the battery pack is also placed here.

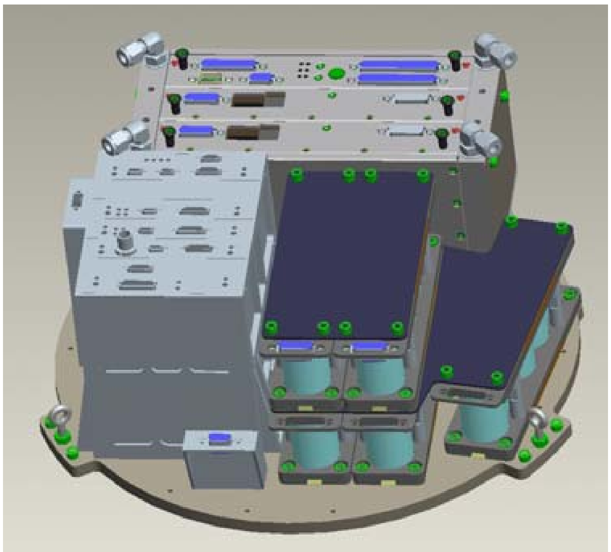

Figure 10. Electronics deck

4.3 Cooling system

Since the sample shall be kept pre-heated for at least 30 minutes during the count-down, an efficient cooling system is needed to keep the module at ambient temperature until lift-off and to maintain temperature during flight.
The primary cooling system consists of an external thermal loop passing through an internal heat exchanger with a fan. Since the module is pressurized during flight this fan can be used to provide temperature transport between “hot” and “cold” parts also after lift-off when the external cooling is removed.
In addition to this an internal cooling loop is at hand. This comprises the X-ray tube front plate and two heat exchangers on the electronics deck.

4.4 X-ray protection

The furnace, camera and top of the X-ray tube are enclosed in an X-ray shielded compartment. Access to the furnace is granted via a movable hatch with safety switches that turn off radiation as soon as the hatch is opened.
A connection for external safety switch and warning light is connected to a connector in the outer structure. Radiation cannot be operated without connecting these. At a late point during count-down these safety devices are replaced by an “arm” plug used during flight.
In this way the integrated module can safely be operated without applying external shielding during test and integration.

4.5 Outer structure

The outer structure is made of aluminium with a yellow chrome surface treatment. The module will be pressurized with nitrogen atmosphere during flight and the outer structure is sealed with pressure tight lids in both ends. All hatches, umbilical blocks and access points are also pressure tightened.

5. ELECTRONICS AND CONTROL SYSTEM

5.1 Experiment electronics

The experiment electronics comprise a Temperature Measurement Board measuring the furnace temperatures and a Power Board that deliver two PWM outputs for the furnace heaters and controls the sample movement motor. These boards are microcontroller based and communicate with the Experiment control computer over CAN-bus.

5.2 Control system

The control system is housed in the electronics cabinet on the electronics deck.
The Experiment control Computer is an Atom-based CPU board running QNX real-time operating system. It interfaces the Experiment electronics boards and the Housekeeping board over CAN-bus and the X-ray Control Computer over serial communication. Telemetry and Telecommand is performed via the Maser Service Module (MASM-2) over serial communication.

5.3 Battery system

The battery system consists of a NiMh battery pack with 25 cells and a Housekeeping Board that conditions and monitors the module voltages and currents and other housekeeping data.

6. SUPPORT SYSTEMS

For real time monitoring and control on ground and during flight an Electronic Ground Support System (EGSE) is built. This system consists of: Operator terminals for display of real-time down-linked data and status, and for transmission of control commands. A video down-link system is provided for reception and display of real-time downlinked images. Systems for battery charging and conditioning and for control of the X-ray tube evacuation system.

7. ACKNOWLEDMENTS

This research work is supported by the XRMON project (AO-2004-046) of the MAP program of the European Space Agency (ESA).

8. REFERENCES

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