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IMPACT: A New Device for Thermo-Mechanical Investigation on Central Receiver Materials

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Abstract. An innovative experimental tool for in-situ investigation of thermo-mechanical damage in solar receiver materials is designed and tested. The major benefit of this technique lies in the possibility for the operator to locate and follow the real-time damage evolution of the sample during solar radiation cycling, and to classify the observed mechanisms.

INTRODUCTION

A promising route toward affordable solar energy conversion lies in the development of high temperature Concentrated Solar Power (CSP) towers [1]. The extreme thermal stress conditions to which the tower receivers may be submitted raise the question of its ability to efficiently operate over extended periods of time [2]. Conventional methods commonly used to assess their mechanical stability and lifetime involve laboratory testing, which suffer from their inability to effectively reproduce the real operating conditions. The implementation of an in-situ and non-destructive measurement technique should enable to scrutinize the receiver materials behaviour under real conditions [3]. Among these techniques, acoustic emission has been identified as the most suitable to detect the initiation of defects with a high resolution [4]: the microstructural changes are perceived before dramatic propagation.

In this work, we propose an original setup based on acoustic emission for in-situ thermo-mechanical investigation of receiver materials exposed to concentrated solar radiation. This setup is named IMPACT (In-situ thermo-Mechanical Probe by ACOustic Tracking). Its ability to precisely track the nature, the location and the spread of the defects in the receiver material is assessed, and an example of damage tracking is depicted.

WHAT SETUP FOR A RELIABLE DAMAGE TRACKING IN RECEIVER MATERIALS?

Measurement Technique

Acoustic emission is the phenomenon associated with the generation of ultrasonic transient elastic waves due to the sudden release of energy from local micro-displacement within the microstructure of a material [16]. The emergence of micro-displacements can be induced by mechanical (plastic strain, fracture, delamination, interface sliding, leaks, etc.) or physical and chemical (corrosion, phase change, gassing and grain growth, etc.) *events*. The

resultant waveform signal is called acoustic *hit*. Its principal characteristics are depicted on Figure 1: duration, amplitude, counts (recording threshold overrun), rise time (time to reach the maximum amplitude peak). They can be used to calculate other characteristics such as energy or frequency parameters.

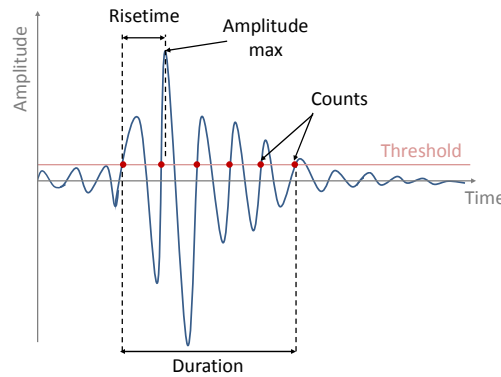


FIGURE 1. Acoustic waveform characteristics.

Acoustic emission (AE) is also, by extension, the test method based on this phenomenon. It is a passive and non-destructive method that can track the real-time microstructural evolution in a component by recording the acoustic hits with piezoelectric sensors placed in contact with the surface. These hits can provide useful information on damage mechanism occurring within the materials based on complementary approaches:

- **The cumulated number of hits** (or released energy) is representative of the damage evolution [5];
- **The hits waveform characteristics** (frequency, amplitude, energy, etc.) can describe a specific type of defect, and their analysis could discriminate the different damage categories [6];
- **The events location** should reveal the damage progression dynamics and could be correlated with the stress concentration zones.

The location can be achieved by triangulation technique, using the hit arrival time of several sensors to deduce event position from the material wave velocity. A 2D location involves at least three sensors. Increasing this number improves the resolution and reduces the sensitivity to potential wave speed variations [7].

Solar Facility

The solar receiver irradiation conditions are reproduced on centimetre-sized samples by a 2 m-diameter parabolic solar furnace (Figure 2), located at PROMES-CNRS laboratory, Odeillo, France.

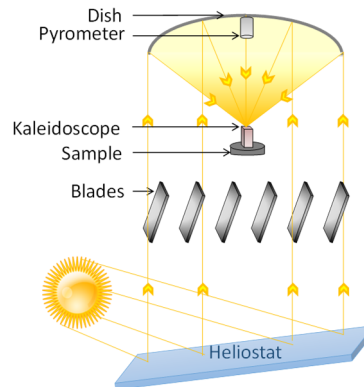


FIGURE 2. Solar facility – 2 m parabolic dish.

The solar irradiation is first collected by a flat heliostat, then reflected on a parabolic dish concentrating the solar flux onto the kaleidoscope entrance, and finally absorbed by the sample located at the kaleidoscope exit. The solar

flux is regulated by fast shutter blades, allowing a precise and repeatable control of the sample irradiation during the thermal cycles for most of the weather conditions. A solar-blind pyrometer is used to measure the front central temperature (measures start at 250°C).

The sample is equipped by the innovative acoustic setup described in the following paragraph.

Setup Design

In order to assess a wide range of mechanical behaviours, the development is conducted considering a brittle material, silicon carbide (SiC α), and a ductile one, Inconel 625, both candidates for CSP receivers [23]. The samples have disk shapes to avoid stress concentrations in corners and to firstly prove the location concept viability in solar receiver operating conditions with a simple geometry.

Three key parameters have been optimized to reach a reliable location in these materials, with by order of influence:

- **The sensors array:** the resolution has been improved by increasing the number of sensors while keeping a regular spacing between them [8], but still limiting the instrumentation bulk;
- **The wave's transmission quality:** acoustic waveguides must be employed to isolate the sensors from high temperatures, but this inevitably degrades the quality of the signal during the propagation between the sample and the sensor. This degradation has been limited with an optimal waveguide shape [9] and by a suitable coupling sample/waveguide (high pressure dry contact) and waveguide/sensor (glue);
- **The location strategy:** as the “arrival-time” technique gives weak accuracy in “dead-zones” (sample surface uncovered by the sensors array), it has been combined with the “first sensor” technique, slightly improving the results. This last technique identifies the closest sensor to the source, delimiting a zone where the event must be located [10].

Acoustic simulations have been carried out in each possible configuration by breaking pencil leads (Hsu-Nielsen test, defined by the EN 1330-9 standard) on specific known locations on the sample disk, and comparing them to calculated ones based on the measurements. These sets of measures led to a 40% reduction of the mean position error, with a final value of 3.5 mm on a 100 mm diameter sample, which is less than 5% error.

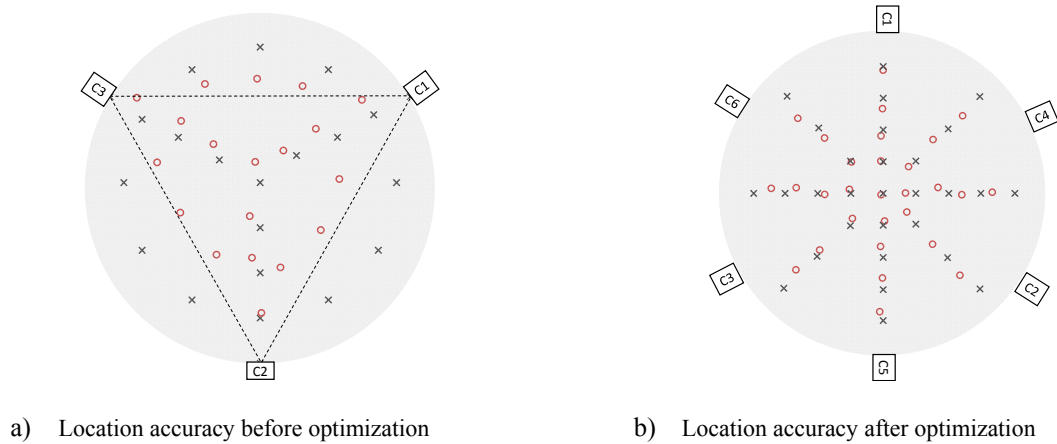


FIGURE 3. Improving the location reliability.

Results are presented in Figure 3 for two extreme cases: a) the basic configuration, with minimum number of sensors, low quality coupling and single location strategy; b) the optimized configuration, with a 6 sensors hexagonal array, high pressure coupling (0.67 N.mm⁻¹ spring), and combined location strategy. The grey circle stands for the sample, the sensors are drawn on its sides, and the acoustic simulation locations are reported: the references at the black crosses and the measurement at the red rings. The sensors array is delimited by the dotted line.

Considering the identified optimum experimental parameters, the IMPACT setup showed in Figure 4 has been designed (left part) and built (right part). The sample is supported by 3 alumina rods, and held by 6 rounded alumina waveguides. The tips of the waveguides are glued to the acoustic sensor using cyanoacrylate glue, and both are held

by a spring. Very thin K-type thermocouples are inserted between the sample and the three supporting rods: the sample pressure on the rods ensures a good mechanical contact with the thermocouples, and their small diameter avoids significant thermal disturbances.

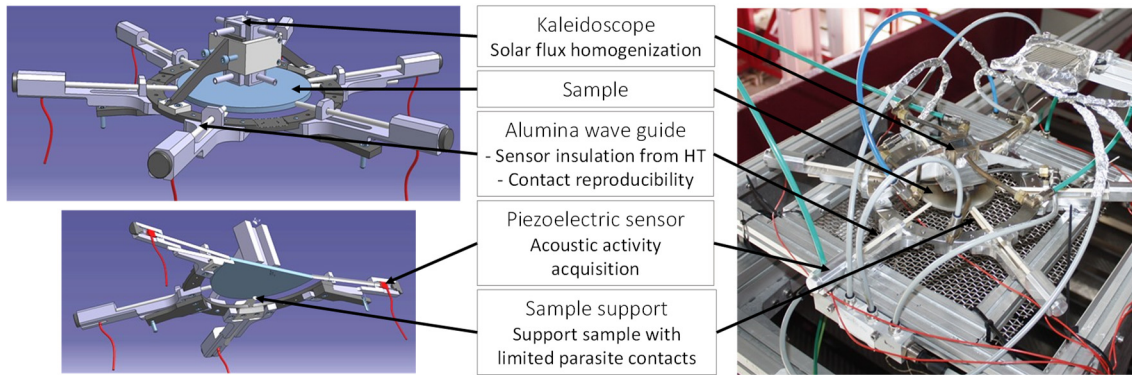


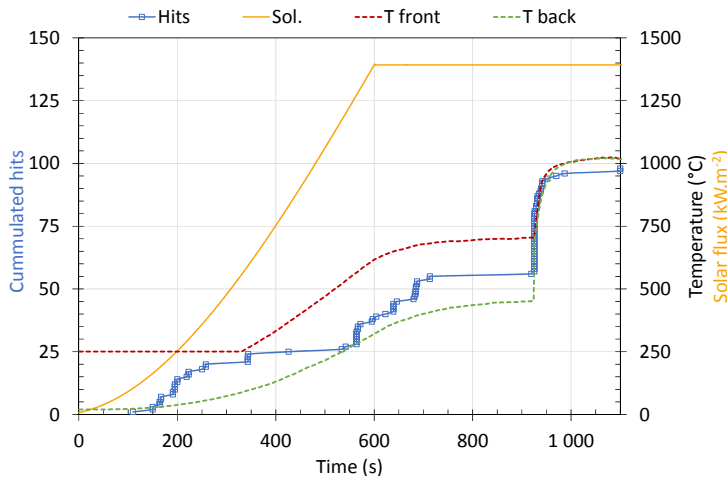
FIGURE 4. Setup with improved location reliability.

ON-SUN EXPERIMENTATIONS

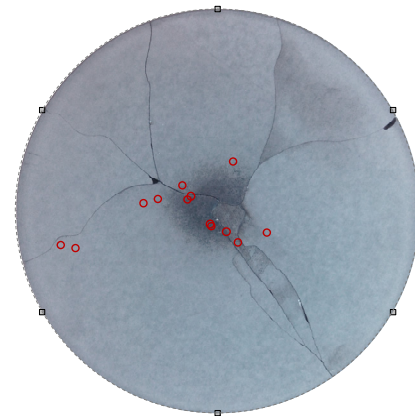
The following on-sun experimentations aim to assess the setup ability to suitably locate and identify the defects occurring in the samples. One disk (100 mm diameter 5 mm thick) of each material has been placed at the focus of the solar furnace, and the blades have been progressively opened ($10\%.\text{min}^{-1}$) until 1400 kW.m^{-2} and 500 kW.m^{-2} respectively for SiC sample and Inconel 625 sample which had been pre-oxidized beforehand at 1100°C .

Test on SiC

The thermal and acoustic behaviour of SiC during the test is depicted on Figure 5. On the graph Figure 5.a), the applied solar flux (yellow line), the measured front and back temperature (respectively red and green dotted line), and the cumulated acoustic hits (blue line with squares) are plotted as a function of time.



a) Temperature and acoustic activity evolution during test



b) Sample picture and hits location

FIGURE 5. Test on a 100 mm diameter SiC sample: behaviour under exposure.

During this test, the SiC sample failed due to a cold point created by a kaleidoscope misplacement, creating a high stress level in a local zone. The time corresponding to the sample breakdown can be identified by the sudden

temperature rise (occurring at ~950s) which is associated with the rapid heating of the SiC piece remaining at the focus after the sample destruction. Figure 5.b) displays the located events and the crack pattern, from a failure initiated on the sample centre: the initial crack is supposed to be the one describe by the hits. An oxidation zone on the exposed part to the sun is visible.

The acoustic activity recorded before the sample failure reveals the setup ability to track the damage evolution before dramatic cracks. Only a part of the hits has been located as events, most probably due to discrepancy in coupling quality or to errors in wave velocity calculation. However, the located events clearly follow the crack pattern, demonstrating the ability of the setup to accurately locate events related to damage initiation and propagation.

Test on Inconel 625

The thermal and acoustic behaviour of Inconel 625 during the test is depicted on Figure 6. On the graph Figure 6.a), the applied solar flux (yellow line), the measured front and back temperatures (respectively red and green dotted line), and the cumulated acoustic hits (blue line with squares) are plotted as a function of time. The cumulated number of hits increases regularly before 6400s, after what they stop to appear: that should correspond to a stabilization in sample microstructure face to the constant solar flux radiation. Figure 5.b) displays the located events, mainly found on the sample centre.

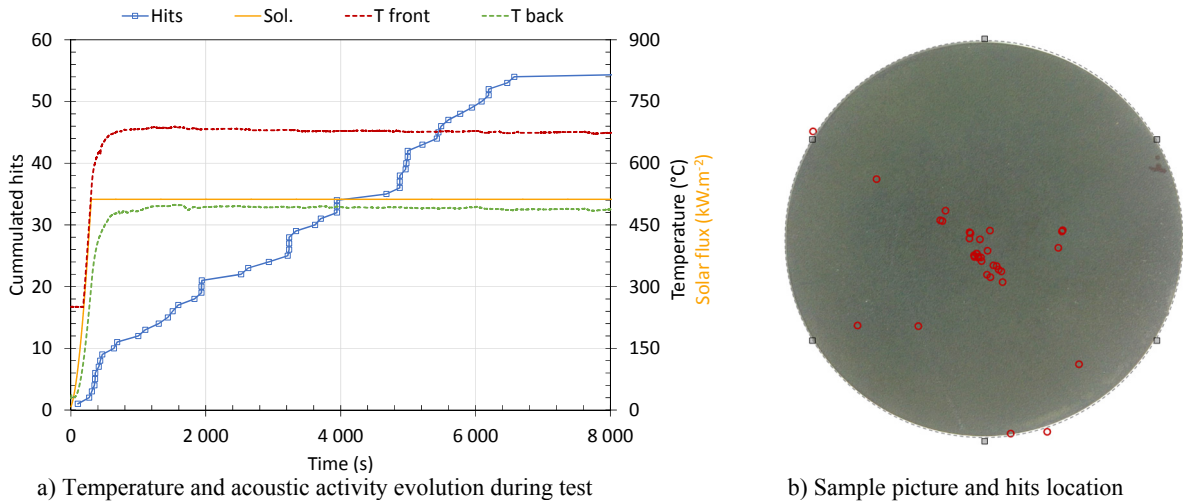


FIGURE 6. Test on a 100 mm diameter Inconel 625 sample: behaviour under exposure

The Inconel 625 acoustic activity is less profuse than the SiC one, but a slightly higher proportion of the hits has been located. Three of them are situated up to 1 mm outside the sample: that is obviously an error, but underlying the setup ability to locate events in the “dead-zone”.

Acoustic Hits Analysis

The category of the events generating the acoustic activity can be identified by scrutinizing the hits characteristics. When the hits amplitude of the located events in both samples are plotted as a function of their duration (Figure 7), different groups or clusters can be visually delimited. The Group 1 contains mainly hits from SiC (only one of Inconel 625), with high amplitude (between 40 and 50 dB) and low duration (20 μ s on average): these characteristics generally describe a fissuring phenomenon [11]. Even if Inconel 625 sample did not show any crack, that could be micro-crack generated in the pre-existing oxide layer. The Group 2 contains exclusively hits from Inconel 625 sample, with a mean amplitude slightly lower (around 37 dB) and notably higher duration (2500 μ s on average): these characteristics generally describe plasticity phenomenon [11]. The Group 3 contains exclusively hits from SiC, with regular amplitude and duration (lower than 34 dB and with a mean duration of 670 μ s). These hits shows as well a low rise time (less than 200 μ s), and then could be a crack propagation phenomenon [12]. The Group 4 also contains

exclusively hits from SiC, with low amplitude and duration (less than 36 dB and with a mean duration of 10 μ s). Besides, their feeble absolute energy (around 1 aJ) suggests an oxidation phenomenon [13].

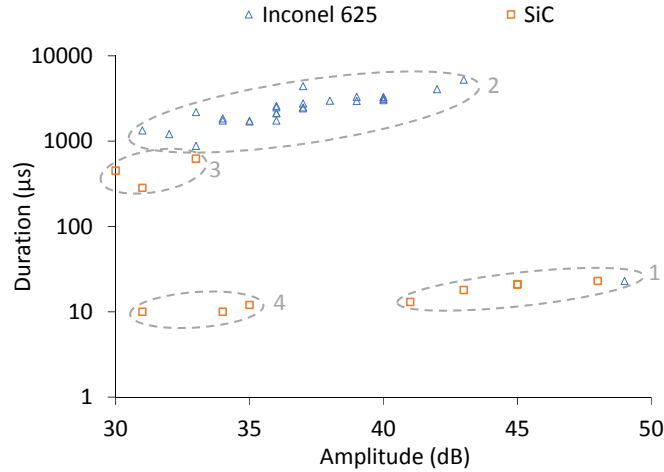


FIGURE 7. Duration vs Amplitude of recorded hits – SiC (orange squares) and Inconel 625 (blue triangles)

These tests validated the ability of IMPACT to apply the required solar radiation onto test-samples and to simultaneously record the sample temperatures and acoustic emission characteristics. The possibility of diagnosing damage evolution in materials submitted to thermal shock is of uttermost importance for the CSP field in general [14], but also for other high temperature domains, such as glass or steel furnaces [15], turbines [16], aeronautics [17], etc.

CONCLUSIONS

In this paper, a new original device for in-situ thermo-mechanical investigation on CSP receiver materials has been presented. The strength and the novelty of this method, based on acoustic emission, lie in its ability to detect microstructural changes and defects at an early stage in real operating conditions.

We identified several key parameters which were optimized to achieve high location accuracy: 1) hexagonal sensors array, 2) no coupling contact between sample and waveguide 3) high pressure spring, and 4) combined time arrival and zonal location.

We experimentally demonstrated, using the IMPACT experimental setup developed in the framework of this study, the ability of this method to better understand the thermo-mechanical behaviour of solar receiver materials in real operating conditions. This ability could be used to run tests on a wide range of materials to assess their comparative damage behaviour. A second step could be to scale up the device to monitor plant receivers in operation.

An accurate detection of the degradation mechanisms occurring in the sample under test will necessarily require the optimal cycling strategy to be determined. The hits identification should be improved using dedicated statistical methods. In addition, the acoustic activity will have to be precisely correlated to the solar cycles, to better grasp the material behaviour under extreme thermo-mechanical stress and to assess their durability in real operating conditions. These perspectives will be addressed in future work.

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