An Elevated-Temperature TSA Furnace Design

Jon Lesniak
Brian Bartel
Stress Photonics Inc.
3002 Progress Road
Madison, WI 53716
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1.0 Introduction

As a component of an Air Force Phase I SBIR contract, significant progress has been made in elevated-temperature, thermoelastic stress analysis (TSA). For the first time, a furnace was designed to address the specific problems of elevated-temperature TSA. The new furnace, dubbed the Stealth Furnace, combined with a new differential thermal imaging array camera, was used to monitor crack growth at elevated temperatures. Although previous work performed by Enke and Lesniak [1] demonstrated the ability of TSA to work at elevated temperatures as high as 1100˚C (2000˚F), there was not a complete understanding of thermal radiation or the problems that hinder high-temperature testing. Applying TSA to extreme environments was still very much a black art that would often fail to yield results. To improve on this, a deeper understanding of the relationship between thermographic methods and the test environment is established in this work.

2.0 Thermoelasticity and elevated temperatures

The main governing equation for TSA is the Thermoelastic Equation:

$$\Delta T = \frac{\alpha T}{\rho C_p}(\Delta\sigma) \tag{1}$$

where T is absolute temperature, α is the coefficient of thermal expansion, ρ is the density, C_p is the specific heat, and $\Delta\sigma$ is the sum of the principal stresses. The material properties should be evaluated at the operating temperature. The dependence on absolute temperature in eq. 1 is of particular importance because as the specimen temperature rises so does the differential temperature induced via the thermoelastic effect. There are many other important details including the relationship between the differential signal and the photon flux and the influence of absolute temperature on the noise photon flux.

Figure 1 shows the result of a detailed thermal radiation model in terms of the signal to noise ratio with respect to temperature. The signal used in this ratio is the photon flux induced by a load that would create a 0.001 K (1.0 mK) temperature oscillation at room temperature. Naturally, as the temperature is increased the same load induces a thermal oscillation exceeding 1.0 mK. The noise is related to quantum statistics of photon emission and is very dependent on specimen temperature. Although ideal performance improves with elevated temperature, the practical performance is less because of electronic saturation problems. These problems occur when the vastly increased flux due to elevated temperature exceeds the design limitations of the IR camera electronics. With these practical limitations, however, a room temperature equivalent S/N is attained at very high temperatures.

3.0 Pseudo-Signal Sources

Considering the thermoelastic relation, radiation theory and IR camera design, there should be little difficulty performing elevated-temperature TSA (however, anyone experienced in elevated-temperature TSA would have a different opinion). There is a set of physical phenomena associated with elevated-temperature work referred to as pseudo-signals. Pseudo-signals are fluctuations in the radiance that by their nature are not separable from the true signal. All of the pseudo-signals found are coupled to the small motions caused by natural elastic extension of both the specimen and the load cell. They are

- Thermal gradients on specimen
- Emissivity gradients coupled with internal reflections
- Angular motion coupled with background gradient
- Edge effects

3.1 Thermal Gradient On Specimen

Thermal gradients on the specimen have two effects. Most obvious is the dependence of the thermoelastic effect on absolute temperature. Roughly, at 750˚C (1380˚F) a 5˚C thermal gradient will result in less than a 1% signal change. Figure 2 demonstrates the more severe effects that occur when thermal gradients combine with specimen motion. The temperature changes induced by the thermoelastic effect are in phase with the stresses imparted by the load. The accumulation of strains resulting in local translations of the specimen is also in phase with the stresses. With the existence of a thermal gradient, the in-phase translation of the specimen results in the in-phase increase and decrease of the absolute temperature of the sampled area. Assuming constant emissivity, the pseudo-signal related to a thermal gradient is roughly described by

$$\Delta T_{ps} = -\frac{\partial T}{\partial d}\Delta d \qquad (2)$$

The following example demonstrates that with even modest specifications a significant pseudo-signal results.

Example: Thermal Gradient

$\frac{\partial T}{\partial d} = 0.4 K/cm$

$\Delta d = 25 \mu m$ (typical load cell deflection at 20% capacity)

$\Delta T_{ps} = 1 mK$ (resolution of SPATE 9000)

3.2 Emissivity Gradient on Specimen

A variance in the emissivity directly attenuates the amount of signal photons emitted from the specimen, but even worse, a small emissivity gradient coupled with specimen motions can cause pseudo-signals. This concept is based on the principle that if a body doesn't emit, it reflects. Two examples stem from this concept: first, the possibility that the camera sees an internal reflection of the furnace wall (Figure 3a), and second, that the camera sees a reflection of itself (Figure 3b).

Assuming constant temperature, the pseudo-signal due to an emissivity gradient is described by

$$\Delta T_{ps} = \frac{\partial \varepsilon}{\partial d}\left(T_s - T_f\right)\Delta d \qquad (3)$$

where T_S is the specimen temperature and T_f is the furnace temperature. As depicted in Fig. 4, as the lower emissivity area is pulled down into the view of the camera, an increase in the wall reflection occurs. As the higher emissivity area is pushed up into the view of the camera, a decrease in wall reflection occurs that appears to be a decrease in temperature. If the specimen and wall temperatures are not matched, a pseudo-signal is generated in phase with the loading. As shown in the following examples, even when modest values of emissivity gradients are used, the effects can be significant.

Example: Reflections from Furnace

$\frac{\partial \varepsilon}{\partial d} = 1\%$ over 2.5mm

$(T_s - T_b) = 10K$

$\Delta d = 25\mu m$

$\boxed{\Delta T_{ps} = 1mK}$ (resolution of TSA)

Example: Self Reflection

$\frac{\partial \varepsilon}{\partial d} = 1\%$ over 2.5mm

$(T_s - T_d) = (1273K - 77K) \approx 1200K$

$\Delta d = 25\mu m$

$\Delta T_{ps} = 120mK$

3.3 Specimen Rotation

Specimen rotation is similar to an emissivity gradient. If the specimen rotates even a slight amount, which often occurs in modal analysis tests, the area of background that is reflected will change. If the background is not a uniform temperature and has a thermal gradient, an in-phase pseudo-signal will occur described by

$$\Delta T_{ps} = 2\alpha L(1-\varepsilon)\frac{\partial T_b}{\partial d} \tag{4}$$

where α is the specimen rotation, L is the distance to the furnace wall, and T_b is the average background temperature over the blurred reflection area. The background gradients can be large when the edge of a furnace window is involved.

3.4 Edge Effects

Edge effects can generate the most severe pseudo-signals. As depicted in Figure 5, edge effects occur when the sample area lies partially on and partially off the specimen. If the specimen and wall temperatures are not closely matched, any specimen motion will cause a significant pseudo-signal. The edge effect is described by

$$\Delta T_{ps} = -\frac{\partial A_{spot}}{\partial d}\frac{(T_s - T_w)}{A_{spot}}\Delta d \tag{5}$$

where A_{spot} is the spot size of the detector as imaged on the specimen, Δd is the amount the edge moves, and the partial derivative describes the change in spot area covering the specimen as a function of edge motion.

Example: Edge Effect

$$A_{spot} = 0.04\text{mm}^2$$

$$\frac{\partial A}{\partial d} = 0.2\text{mm}^2/\text{mm}$$

$$\Delta d = 25\mu\text{m}$$

$$\left(T_s - T_w\right) = 1\text{K}$$

$$\Delta T_{ps} = 125\text{mK}$$

This, of course, far exceeds the desired resolution of TSA.

4.0 Furnace Layout And Control

The new, optimized furnace is designed considering all of the pseudo-signal sources. The furnace is laid out in four zones (Figure 6). Zones 1 and 2 are wall heaters, where zone 2 includes the wall behind the specimen. Zones 3 and 4 control the temperature of the specimen, compensating for the conduction of heat through the specimen and into the grips.

A computer program monitors the temperatures allowing individual adjustment of the power duty cycle. Duty cycles are varied by triggering solid-state relays with the voltages from four bits of a digital output. This control system was able to control the zonal temperatures to within ±2 K, which is adequate for minimizing the pseudo-signals described above.

4.1 Reducing Reflection Problems

Two features of the furnace help reduce the self reflection and the specimen rotation problem. First, the deep triangular shape of the furnace (Figure 6) pulls the window farther from the specimen and closer to the camera. This minimizes the solid angle subtended from the specimen to the window. Second, the specimen is angled so that reflections will primarily come from the zone 1 wall instead of from the external environment, in particular the camera.

4.2 Reducing Wall Reflections

Because the furnace is designed to force reflections to zone 1, care must be taken to minimize wall reflections. This is accomplished by forcing zone 1 to closely match the specimen temperature. Because the specimen and zone 1 temperatures are matched, the specimen either emits at the control temperature or reflects zone 1, which is also at the control temperature. By Eq.

3, motion of an emissivity gradient will not cause a change in the background radiance and therefore, no pseudo-signal is generated. Because the specimen is cooled by conduction through the grips, it is actually the zone 3 and zone 4 heaters that drive the specimen temperature up to the control temperature.

4.3 Reducing Thermal Gradients

The control of thermal gradients is quite simple. The heating elements of zone 3 and 4 are independently controlled and monitored so that no thermal gradient above 0.4 K/cm exists. Figure 7a is a DC (absolute temperature) image of the specimen surface without zone 3 or 4 heaters on. Notice the zone 3 thermocouple peeking out above the heater. Figure 7b shows the DC thermal image with zone 3 and zone 4 heaters in control of the gradient.

4.4 Reducing Edge Effects

Zone 2 is also controlled to match the specimen temperature to reduce edge effects. It is very difficult to control elevated temperatures within a few degrees, so it is unlikely that all of the edge effect can be prevented.

5.0 Furnace Results

Figure 8 shows the specimen that was scanned at high temperature. Although the prototype furnace can achieve about 750˚C (1400˚F), the choice of 1018 steel specimens did not permit this extreme. The maximum temperature attained was about 482˚C (900˚F). Figure 9a shows a room temperature scan with a similar specimen, and Figure 9b is a high-temperature scan. The comparison between room temperature and high temperature was easier using the array camera's near real-time video output. The room-temperature video showed a randomly changing pattern of noise. When using the Stealth Furnace and thereby limiting thermal gradients, emissivity gradients, and edge effects, the video output showed a more stable image.

References

1. Enke, N., Lesniak, J.R., Sandor, B.I., "High-Temperature Stress Analysis Using Differential Infrared Thermography," SEM Fifth Annual Hostile Environments and High Temperatures Measurements Conf., Costa Mesa, March 1988, pp. 4-7.

List of Figures

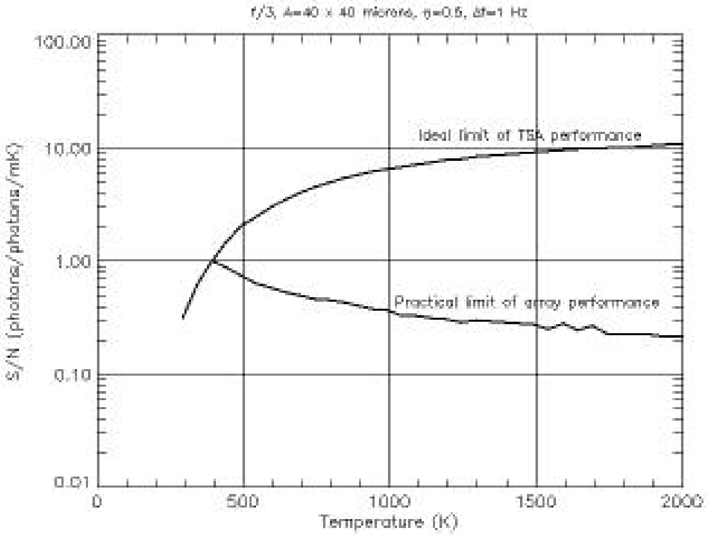


Fig. 1 S/N vs. temperature for TSA (Ideal performance compared to Array performance).

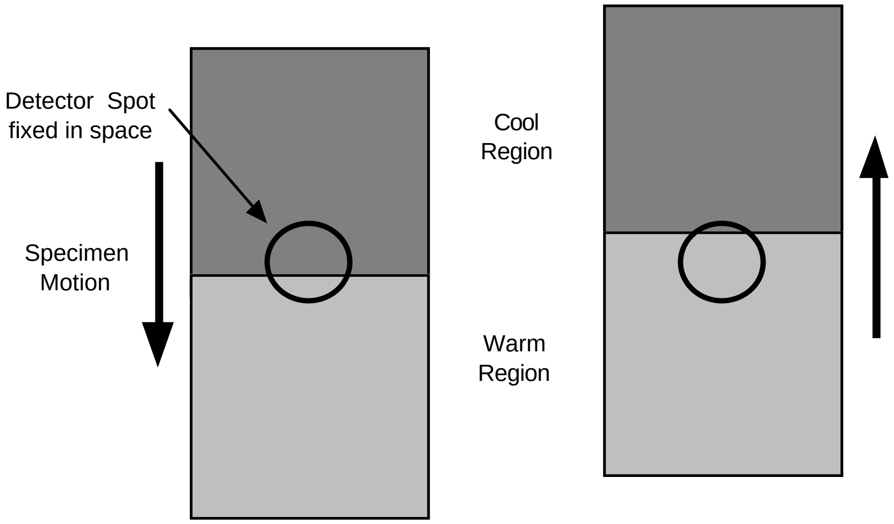
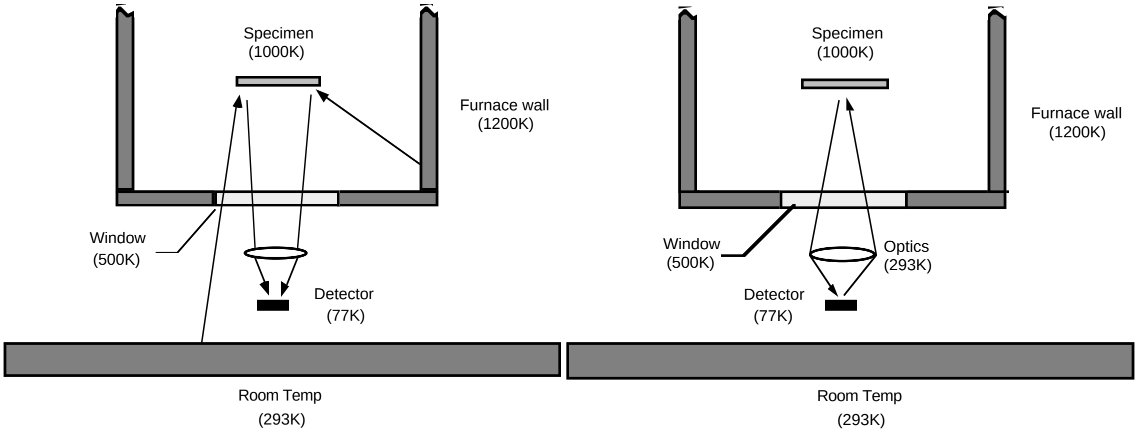


Fig. 2 Thermal gradients coupled with specimen translation.



(a) wall or surroundings reflection

(b) self reflection

Fig. 3 Reflections.

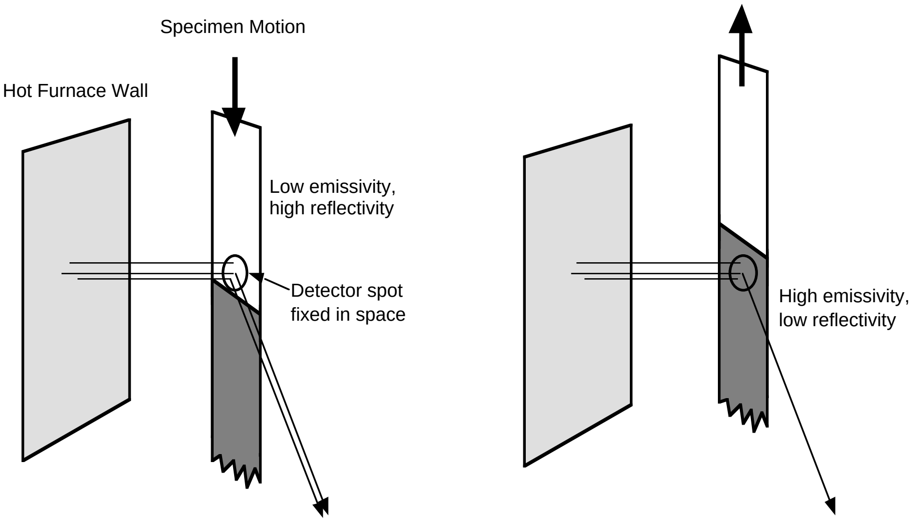


Fig. 4 Effects of emissivity gradient.

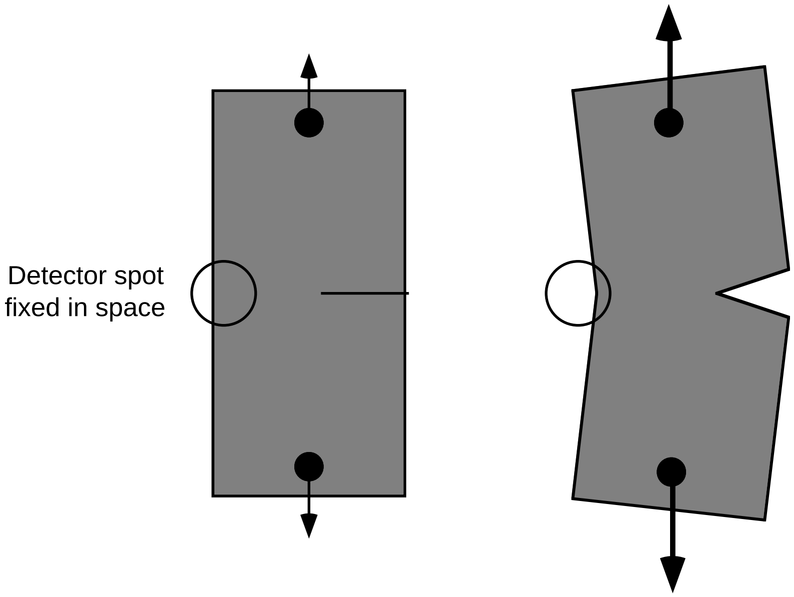
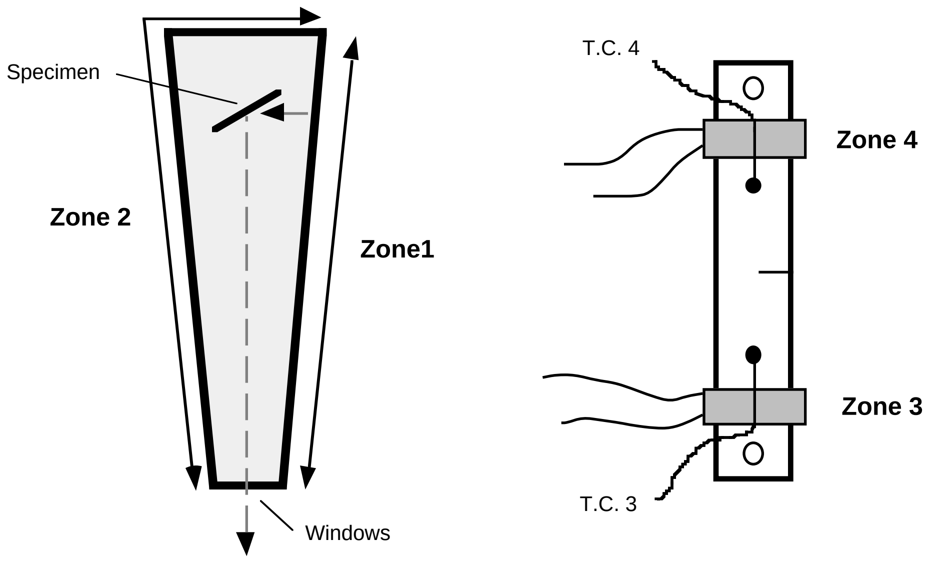
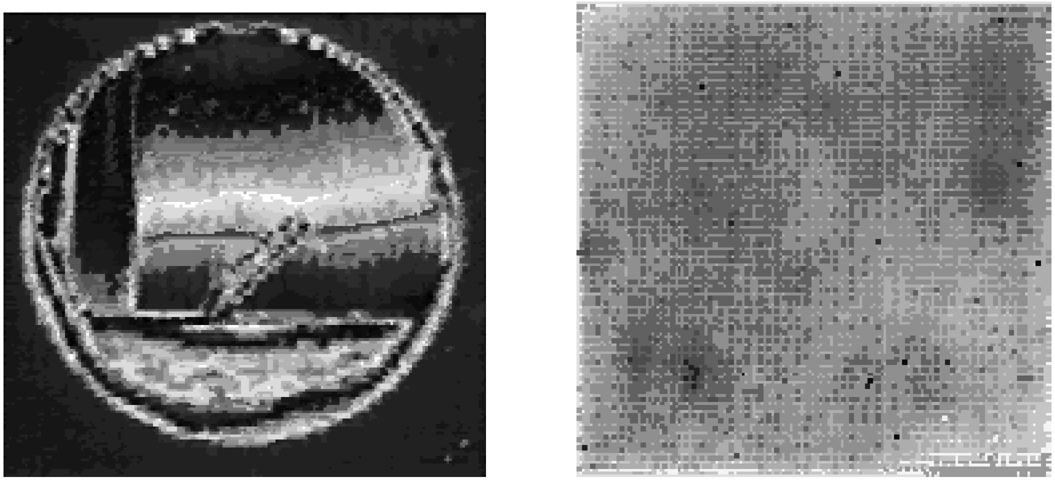


Fig.5 Edge effects.



(a) top view of furnace (b) front view of specimen

Fig. 6 Furnace layout.



(a) specimen heaters off (b) specimen heaters on (close up)

Fig. 7 High-temperature DC images.

Both images are similarly scaled for a qualitative comparison.

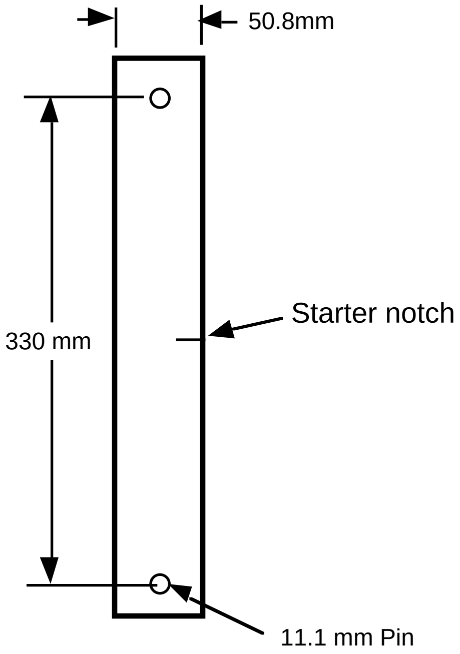
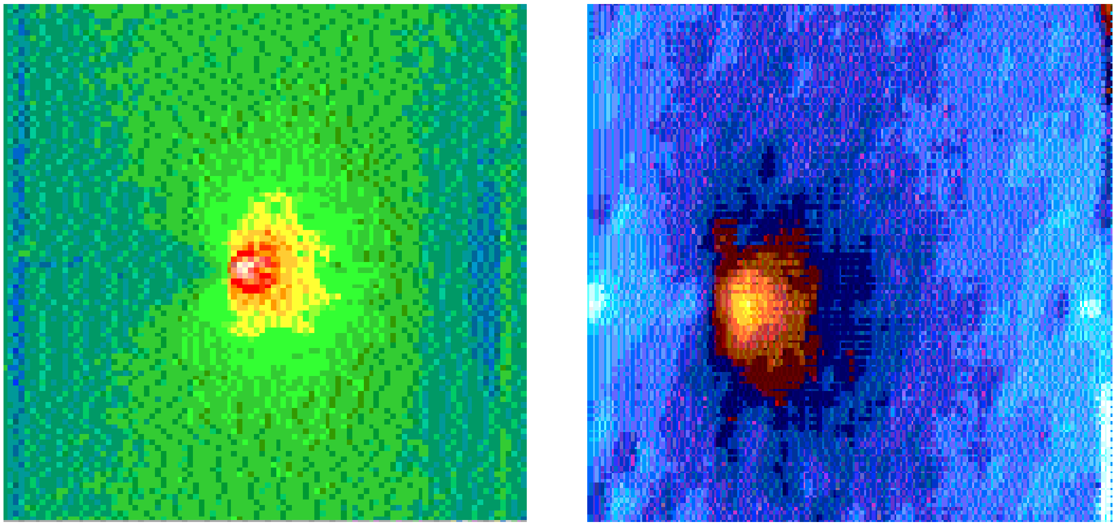


Fig.8 High-temperature specimen configuration.



(a) room-temperature stress image (b) high-temperature stress image (482˚C)

Fig. 9 Room-temperature vs. high-temperature images of crack region in plate.

Both images are similarly scaled for a qualitative comparison.