Principles of high speed thermography

application on the study of adiabatic shear band initiation

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Outline

Introduction : adiabatic shearing
Thermography principles and design
Temperature measurement with thermography
Temperature measurement during the onset of an ASB
Conclusion

1. Introduction : adiabatic shearing
   - An example
   - The physical mechanisms
2. Thermography principles and design
   - Radiation of solids
   - Thermographic device
   - Calculation of the output signal of the detector
   - Noise and detector limitations
   - Noise equivalent temperature difference
3. Temperature measurement with thermography
   - Calibration
   - Effect of the emissivity on the temperature estimation
4. Temperature measurement during the onset of an ASB
   - Experimental device
   - Experimental results
5. Conclusion

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Armour perforation - adiabatic shear bands

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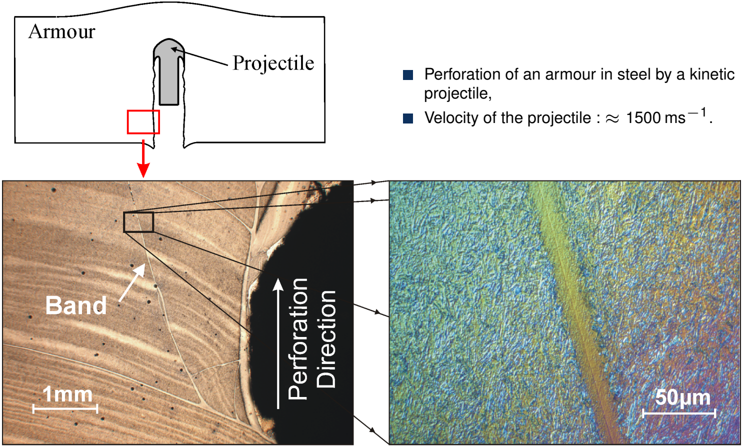

Observation of ASB with optical microscopy

Enlargement

- Perforation of an armour in steel by a kinetic projectile,
- Velocity of the projectile : $\approx$ 1500 ms^{-1}.

Onset of a plastic strain localization : adiabatic shear band

Adiabatic shearing - the physical mechanisms

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History

- Discovery of the phenomena by Tresca in 1978 during metal forging
- Mechanism proposed by Zener et Hollomon in 1944

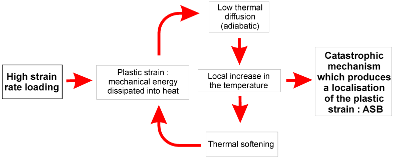

FIGURE : Mechanism of an adiabatic shear band formation according to Zener and Hollomon, 1944

Two temperature domains in an ASB

- **"Low temperatures"** during the initiation of an ASB ; $T \approx 100$ ℃, characteristic size : $\approx 50\,\mu$m, characteristic time : $\approx 1\,\mu$s.
- **"High temperatures"** in a fully formed ASB : $T \approx 1000$ ℃, characteristic size : $\approx 5\,\mu$m, characteristic time : $\approx 1\,\mu$s.

Experimental results

- Marchand and Duffy observed ASB during dynamic torsion using Split Hokinson bars in 1988

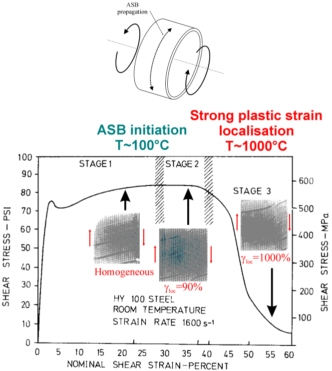

FIGURE : Initiation stages of an ASB according to Marchand and Duffy, 1988 .

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Radiation of solids

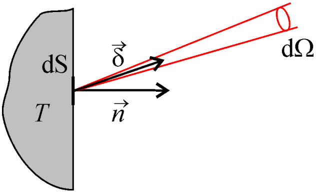

FIGURE : Radiation of a surface.

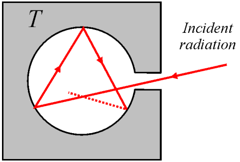

FIGURE : Black-body : thermostatted cavity.

Radiated power by the surface

- Emitted power by the surface dS in a solid angle dΩ in the direction $\vec{\delta}$:

$$d\mathcal{P} = R(\vec{\delta})\vec{\delta}.\vec{n}\,d\Omega\,dS$$

with R the radiance.

- Spectral radiance R_λ :

$$R_\lambda = \frac{dR}{d\lambda}$$

Spectral radiance

- case of a black-body (absorb all incident radiations : perfect emitter), Planck's law :

$$R^0_\lambda(T,\lambda) = \frac{C_1\lambda^{-5}}{\exp\frac{C_2}{\lambda T} - 1}$$

- Non linear law according to the temperature !
- Real surface case :

$$R_\lambda(T,\lambda) = \varepsilon(T,\lambda,\ldots)R^0_\lambda(T,\lambda)$$

- ε is a thermo-optical property of the surface which depends on the temperature, the wavelength, the material and the characteristics of the surface...

Black body radiance : maximum of the radiance

Spectral distribution of the radiance

- Spectral radiance

$$R^0_\lambda(T,\lambda) = \frac{C_1\,\lambda^{-5}}{\exp\frac{C_2}{\lambda T} - 1}$$

Maximum of the emitted power

- Wien's displacement law

$$\lambda_{max} = \frac{C_2}{5}\,\frac{1}{T}$$

- Examples
  - 77 K : $\lambda_{max} = 38\,\mu m$
  - 100 °C : $\lambda_{max} = 8\,\mu m$
  - 1000 °C : $\lambda_{max} = 2\,\mu m$
  - 1600 °C : $\lambda_{max} = 1\,\mu m$

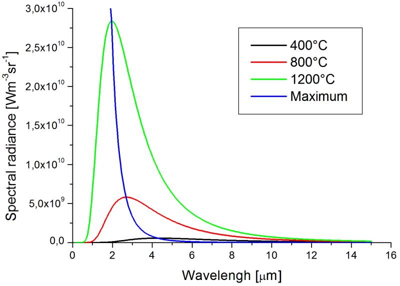

FIGURE : Spectral distribution of radiance.

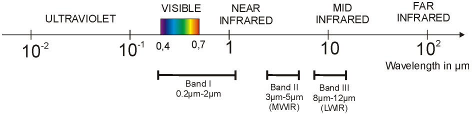

FIGURE : Wavelength of thermal radiation.

Sensibility to a temperature variation

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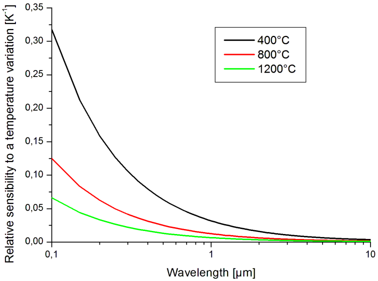

FIGURE : Relative sensitivity to a temperature variation.

- Relative sensitivity to a temperature variation :

$$\frac{1}{R_\lambda^0}\frac{\partial R_\lambda^0}{\partial T} = \frac{C_2}{\lambda T^2}\frac{\exp\left(\frac{C_2}{\lambda T}\right)}{\exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

For $T = 100$ °C ; $\lambda = 12$ µm (Band II ; maximum of radiance)

- Relative sensitivity :

$$\frac{1}{R_\lambda^0}\frac{\partial R_\lambda^0}{\partial T} = 0.0015\,\mathrm{K}^{-1}$$

For $T = 100$ °C ; $\lambda = 3$ µm (Band I ; "short wavelength")

- Relative sensitivity :

$$\frac{1}{R_\lambda^0}\frac{\partial R_\lambda^0}{\partial T} = 0.0042\,\mathrm{K}^{-1}$$

- **Sensitivity almost 3 times higher**

Choice of the shorter wavelength in order to maximized the relative sensitivity

Radiance fluctuations

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Random nature of photon emission

- Photon emission is a random process : the photon emission follows a Poisson distribution
- Mean value according to time of radiance is given by the Planck's law for a black-body :

$$R^0_\lambda(\lambda, T) = \frac{1}{\Delta T}\int_t^{t+\Delta t} r^0_\lambda(t)\mathrm{d}t \quad (1)$$

- The fluctuations of intensity are characterized by the mean square root (white noise) :

$$\overline{(\delta r^0_\lambda)^2} = \frac{1}{\Delta t}\int_t^{t+\Delta t}\left(r^0_\lambda(t) - R^0_\lambda\right)^2 \mathrm{d}t \quad (2)$$

$$= kT^2 \frac{\partial R^0_\lambda}{\partial T} \quad (3)$$

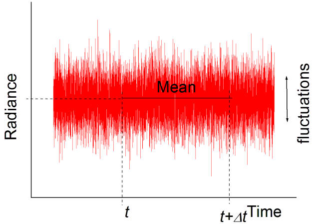

FIGURE : Representation of the fluctuation of the radiance.

Radiance fluctuations

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An numerical application

- For a temperature of 100 ℃, the spectral radiance is :

$$R_{\lambda}^{0}(5.5\,\mu\text{m}, 100\,℃) = 2.1 \times 10^{7}\,\text{W}\cdot\text{sr}^{-1}\cdot\text{m}^{-3}.$$

- The emitted energy during one microsecond for a solid angle $\Omega = 0.78$ sr, a spectral range $\Delta\lambda = 1$ µm and a surface $S = 43$ µm $\times$ 43 µm is

$$\mathcal{E} = 3.1 \times 10^{-14}\,\text{J}$$

This energy corresponds to 8.6×10^{5} photons.

- The fluctuation of the photon number is 926. This corresponds to 0.11% of the emitted photons.

Conclusion

In the infrared domain, the fluctuations of the signal are often negligible !

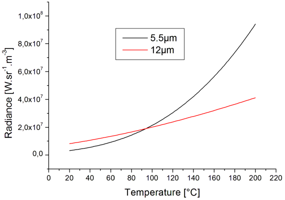

FIGURE : Spectral radiance evolution according to temperature.

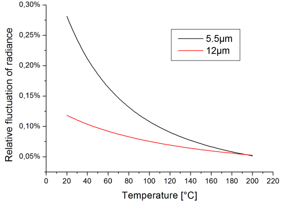

FIGURE : Fluctuation of spectral radiance.

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Thermography, thermographic device composition

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Principle of thermography

- Estimation of the surface temperature according to the radiation of the surface received by a detector

Thermographic device composition

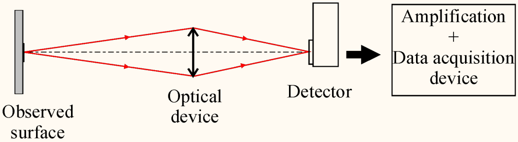

FIGURE : Scheme of a thermographic chain

- **Optical device** : collect the radiation emitted by the surface ; *characteritics* : focal length f ; magnification G (links betwenn the detector surface and the observed surface) ; the aperture $f/\#$ or N allows to quantify the collected energy ;
- **Detector** : convert the incident radiation in an electrical signal which can be measured ; *characteristics* : size of the detector, spectral range, integration time or pass-band.
- **Data acquisition** : digitization (number of digital levels,14 bits...) and recording ; in the case of a CCD captor pixel reading...

Various detector families

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Thermal detectors

- The principle is based on the measurement of the temperature variation generate by the absorption of the incident radiation

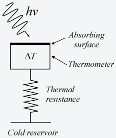

FIGURE : Functioning scheme of a bolometer.

- Various types of thermal detectors :
  - Bolometers (effect of the temperature on the resistivity),
  - Thermopiles (thermocouple),
  - Pyroelectrics (effect of the temperature on the polarisation of a ferro-électric material),
  - ...
- Advantages : « "constant" »spectral response ; high sensitivity if cooled, correct if little cooled
- Disadvantages : response time higher than one millisecond

Quantum detectors

- The quantum detector are sensitive to incident photons. These photons create in the photosensitive material a free electron(called photo-electron) and a hole (positive charge)

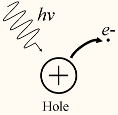

FIGURE : Generation of a pair of electron and hole

- Varoius type of quantum detectors :
  - Photo-emissives (Photomultiplicators tube),
  - **Photoconductors**,
  - **Photovoltaics**,
  - QWIP (Quantum Well Infrared Photodetector),
  - QDIP (Quantum Dot Infrared Photodetector),
  - ...
- Advantages : rapidity, sensibility ;
- Disadvantage : spectral response (cutoff frequency), need to cooled at 77K.

Particularities of high speed thermography

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Limitations of high speed thermography

- Limitations due to the detector and the electronic device :
  - Response time of the detector (In the infrared domain, quantum detectors are used ; typ. 500 ns),
  - Pass-band of the amplification device and sampling frequency of the acquisition device,
  - Case of the matrix devices : reading time of the CCD .
- Limitations due the intensity of the emitted signal :
  - Short integration time and thus low incident signal receive by the detector,
  - Short response time of the thermographic chain : large pass-band and increase of the noise.

case of the adiabatic shear bands initiation study

- a bar of 32 quantum InSb photovoltaic detectors will be used,
- the bar of detector is cooled at 77 K,
- the 32 entries data acquisition allows to measure temperature at a frequency of 1 MHz,
- the size of the detector : 43 µm $\times$ 43 µm ; length of the bar 1.934 mm,
- the optical device characteristics : unit magnification, f/# 2.1.

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Calculation of the incident power on the detector

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Calculation of the power focalized by the lens on the detector

The power radiated by the observed surface dS and focalised by the lens on the detector surface in a spectral band between λ and $\lambda + \mathrm{d}\lambda$ is :

$$\mathrm{d}\mathcal{P} = \iint_{Lens} R_\lambda(\vec{\delta})\vec{\delta}.\vec{n}\,\mathrm{d}S\,\mathrm{d}\lambda\,\mathrm{d}\Omega$$

$$= R_\lambda(\lambda, T) S\,\mathrm{d}\lambda \underbrace{\iint_{Lens} \frac{(\vec{\delta}.\vec{n})^2}{S_1 M^2}\mathrm{d}\Sigma}_{\mathcal{A}}$$

with $\mathcal{A}$ the apparatus constant which depend on the characteristics of the optical device.

Example of a thin convergent lens

$$\mathcal{A} = \pi \frac{1}{1 + 4N^2\left(1 + \frac{1}{G}\right)^2} = \pi \sin^2 \alpha$$

with G and N the magnification and the aperture of the optical device and α the half angle of the lens aperture.

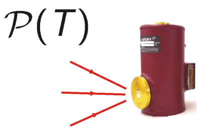

FIGURE : Illustration of $\mathcal{P}(T)$ the power focused on the detector

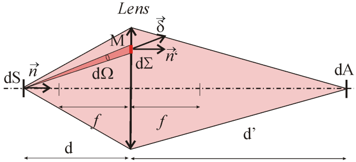

FIGURE : Power focused on the detector

Response of a detector

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Quantum efficiency

The quantum efficiency of a detector is given by the relation :

$$Q(\lambda) = \frac{n_{\text{photoelectron}}}{n_{\text{photon}}}$$

In a quantum detector, it can be close to 100%

Band gap and cutoff wavelength

- to make pass an electron of the valence band to the conduction band, the incident photon must have a sufficient energy :

$$\mathcal{E}_{GAP} < \mathcal{E}_{photon}$$

- to generate a photo electron, the photon must have a wavelength under the cutoff wavelength :

$$\lambda < \lambda_c = \frac{hc}{\mathcal{E}_{GAP}}$$

- case of Indium Antimonide (InSb) : $\mathcal{E}_{GAP} = 0.23$ eV and thus $\lambda_c = 5.4\,\mu$m

Spectral response

The spectral response is defined by : $\mathcal{R}(\lambda) = \frac{dSi}{d\mathcal{P}}$
If Si represents the current generated by the photoelectrons :

$$\mathcal{R}(\lambda) = Q(\lambda)\frac{e\lambda}{hc}$$

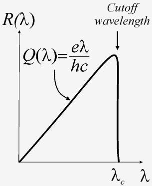

FIGURE : Typical response of a quantum detector

The normalized spectral response is defined as

$$\eta(\lambda) = Q(\lambda)\frac{\lambda}{\lambda_c}$$

Output signal of the detector

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Calculation of the output signal of the detector

For a spectral band between λ and $\lambda + \mathrm{d}\lambda$:

$$\mathrm{d}Si = \mathcal{R}(\lambda)\mathrm{d}\mathcal{P}. \quad (4)$$

With the use of the relation $\mathrm{d}\mathcal{P}$, it can be obtained :

$$\mathrm{d}Si = S_\lambda \mathcal{A} S R_\lambda(\lambda, T)\mathrm{d}\lambda \quad (5)$$

After integration, the total signal Si is :

$$Si = \mathcal{A}S \int_0^\infty S_\lambda R_\lambda(\lambda, T)\mathrm{d}\lambda \quad (6)$$

with $k = \frac{\lambda_c e}{hc}$:

$$Si = Si^0 + k\,\underbrace{\mathcal{A}S \int_0^\infty \eta(\lambda) R_\lambda(T, \lambda)\mathrm{d}\lambda}_{\mathcal{P}_d} \quad (7)$$

with

- Si^0 the offset tension,
- k a constant which depend on the detector,
- $R_\lambda(T, \lambda)$ la spectral intensity of the surface,
- $\mathcal{P}_d = \int_0^\infty \eta(\lambda) R_\lambda(T, \lambda)\mathrm{d}\lambda$ the incident power detected by the detector.

The constants Si^0 and $K = k\mathcal{A}S$ are generally determined during the calibration of the device.

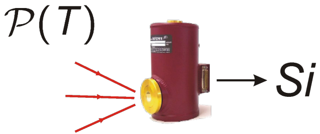

FIGURE : Illustration of the power receive by the detector and the associated output signal

Numerical application

- For the thermographic device for ASB : $\mathcal{A} = 0.048$, the size of the observed surface is $45\,\mu\mathrm{m} \times 45\,\mu\mathrm{m}$
- the numerical calculation of $\int_0^\infty \eta(\lambda) R_\lambda(T, \lambda)\mathrm{d}\lambda$ for InSb detector gives $22.1\,\mathrm{W{\cdot}sr^{-1}{\cdot}m^{-2}}$
- thus

$$\mathcal{P}_d = 0.048 \times \left(45 \times 10^{-6}\right)^2 \times 22,1$$
$$= 2.0 \times 10^{-9}\,\mathrm{W}$$

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Estimation of noise in a IR detector

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Noise in quantum detectors

Various noise sources

- **Thermal noise** (Johnson noise) : electronic noise generated by thermal agitation of of the charge carriers inside an electrical conductor
- **Generation/recombination noise** : noise associated to the statistical fluctuations of the generation and the recombination of the photo-electrons and the holes.
- **Flicker noise** (Pink noise or 1/f noise) : low frequency noise associated to various physical origins (impurities...). Negligible in the case of high speed thermography.
- **Photon noise** : associated to the fluctuations of the number of photons which arrive on the detector. This noise can come from the signal directly or from the background.

Background Limited Infrared Photodetectors (BLIP)

- Except in the case of photon noise, all the other noise decrease when the detector temperature decrease,
- Under the **BLIP temperature**, all the noise are negligible compared to the photon noise associated to the fluctuation of the signal which come from the background fluctuation (**BLIP conditions**),
- For quantum detector InSb the BLIP temperature is higher than 77 K.

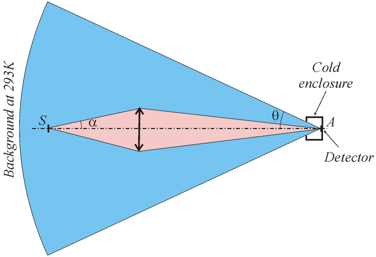

FIGURE : Illustration of a BLIP detector

Characterization of the noise in a detector

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Definition of the Noise Equivalent Power (NEP)

- The Spectral Noise Equivalent Power noted NEP(λ) : input power in a detector associated to a monochromatic incident radiation at the wavelength λ which gives an output signal equal to the noise (rms).

Detectivity and specific detectivity

- The spectral detectivity characterize the performance of a detector and is defined as the inverse of the NEP(λ) :

$$D(\lambda) = \frac{1}{\text{NEP}(\lambda)} \tag{8}$$

The unit of detectivity is W^{-1}. More the detectivity is high, more the detector will be able to detect low signals.

- For the detectors in the BLIP conditions, the spectral detectivity is inversely proportional to the square root of the detector surface and the square root of the passband of the electronical device Δf. The specific spectral detectivity is also define as :

$$D^*(\lambda) = \frac{\sqrt{A}\sqrt{\Delta f}}{\text{NEP}(\lambda)} = D(\lambda)\sqrt{A}\sqrt{\Delta f} \tag{9}$$

The specific detectivity is expressed generally in $\text{cm}\cdot\sqrt{\text{Hz}}\cdot\text{W}^{-1}$ (equally called Jones).

Characterization of the noise in a detector

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Maximum of the specific detectivity

- D^*_{max} or more simply noted D^* is defined as the maximum of the specific dectectivity $D^*(\lambda)$ over the whole spectral band of the detector.
- This maximum is generally obtain for wavelength close to the cutoff wavelength λ_c.

Detector	Cutoff wavelength	Specific detectivity in $\mathrm{cm} \cdot \sqrt{\mathrm{Hz}} \cdot \mathrm{W}^{-1}$
InSb	5.5 µm	$8,97.10^{10}$
HgCdTe	14 µm	$2,89.10^{10}$

TABLE : Specific detectivity of various detector (aperture : 180°; sensitive surface : 1 cm^2 ; pass-band : 1 Hz ; background temperature : 293 K).

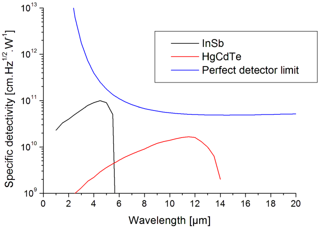

FIGURE : Comparison of InSb and HgCdTe detectors ($T_{background} = 293$ K and $\theta = 90$°).

Effect of detector aperture

Detectivity for an aperture with an half angle θ noted $D^*(\lambda, \theta)$ can be deduced from the specific detectivity $D^*(\lambda, \frac{\pi}{2})$:

$$D^*(\lambda, \theta) = \frac{D^*(\lambda, \frac{\pi}{2})}{\sin \theta}$$

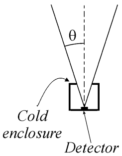

FIGURE : Aperture of a detector.

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Example of NEP calculation

Example

Calculation of the noise of an InSb detector with a size of 43 µm $\times$ 43 µm with a specific detectivity $D^* = 8.9\,\text{cm}\cdot\sqrt{\text{Hz}}\cdot\text{W}^{-1}$ and a pass-band of $\Delta f = 1$ MHz ?

- The noise equivalent power is :

$$\text{NEP} = \frac{\sqrt{A}\sqrt{\Delta f}}{D^*} = \frac{43 \times 10^{-6}.10^2.\sqrt{10^6}}{8,9.10^{10}} = 4.8 \times 10^{-11}\,\text{W} < 2.0 \times 10^{-9}\,\text{W} \quad (10)$$

The noise is lower than the signal receive by the detector !

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Noise equivalent temperature difference

and

signal to noise ratio

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Definition and calculation of NETD

- An infra-red thermographic device is often characterized by the noise equivalent temperature difference (NETD).
- The NETD is the temperature variation which correspond to a variation of signal to noise ratio equal to the unit :

$$\Delta S/N = \frac{\Delta \mathcal{P}_s}{\mathcal{P}_b} \qquad (11)$$

with $\Delta \mathcal{P}_s$ the variation of the power detected by the captor for a temperature variation ΔT and $\mathcal{P}_b$ the power associated to the noise.

- The power receive by the detector

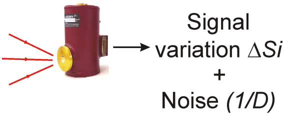
$$\Delta \mathcal{P}_s = S \mathcal{A} \Delta T \int_0^{\lambda_c} \eta(\lambda) \frac{\partial L_\lambda}{\partial T}(\lambda, T) \mathrm{d}\lambda, \qquad (12)$$

- The noise of the detector

$$\mathcal{P}_b = \frac{\sqrt{A}\sqrt{\Delta f}}{D*(T_{fond}, \alpha)}. \qquad (13)$$

- Thus, the NETD is

$$\mathrm{NETD} = \frac{\frac{\sqrt{A}\sqrt{\Delta f}}{D*(T_{fond}, \alpha)}}{S\mathcal{A} \int_0^{\lambda_c} \eta(\lambda) \frac{\partial L_\lambda}{\partial T}(T) \mathrm{d}\lambda} \qquad (14)$$



Noise equivalent temperature difference

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Expression of NETD

The NETD is thus :

$$\mathrm{NETD} = \frac{\sqrt{A}\sqrt{\Delta f}}{S\mathcal{A}D^{*}(T_{fond}, \alpha) \int_0^{\lambda_c} \eta(\lambda) \frac{\partial L_\lambda}{\partial T}(T) \mathrm{d}\lambda} \quad (15)$$

The NETD depends on :

- the pass-band (Δf) ;
- the characteristics of detector : $D^{*}(T_{background}, \alpha)$ and A ;
- the background temperature : $T_{background}$;
- the optical device characteristics like the apparatus constant $\mathcal{A}$;
- the measured temperature T.

Numerical application

For $\mathcal{A} = 0,042$, the magnification $G = 1$, the size of the detectors 43 µm $\times$ 43 µm, the measured temperature $T = 100$ ℃, the background temperature $T_{fond} = 20$ ℃, the detector aperture $\alpha = 60°$, the cutoff wavelength $\lambda_c = 5.5$ µm, the specific detectivity $D^{*}\left(T_{background}, \frac{\pi}{2}\right) = 8.97 \times 10^{10}$ cm$\cdot\sqrt{\mathrm{Hz}}\cdot$W^{-1} and pass-band $\Delta f = 1$ MHz :

$$\mathrm{NETD} \approx 1.1 \text{ ℃} \quad (16)$$

Comparison of the MWIR and LWIR spectral band

- Signal to noise ratio - choice between spectral band II (MWIR : 3 µm-5 µm) and band III (LWIR : 8 µm-12 µm)

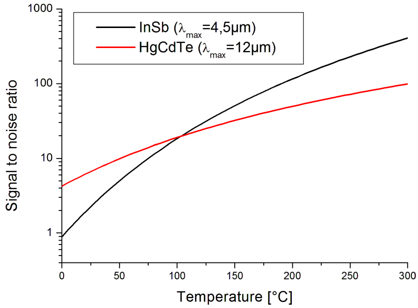

FIGURE : Signal to noise ratio (detector surface : 43 µm × 43 µm ; magnification : 1 ; detecture aperture 60° ; optical aperture : 3 ; pass-band 1 MHz)

Choice of band II is correct for ASB initiation application

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Comparison of the MWIR and LWIR spectral band

- the signal variation associated to a temperature variation of 1 ℃ over the noise

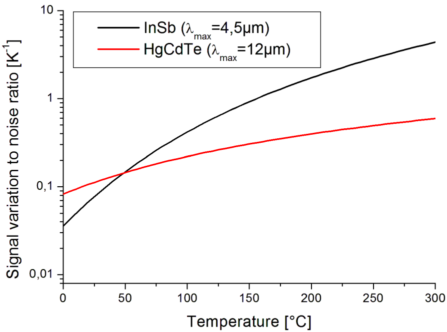

FIGURE : Signal variation to noise ratio (detector surface : 43 µm × 43 µm ; magnification : 1 ; detector aperture 60° ; optical aperture : 3 ; pass-band 1 MHz

Choice of band II is correct for ASB initiation application

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Calibration of the thermographic device

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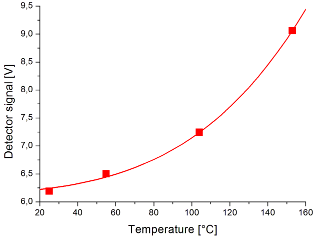
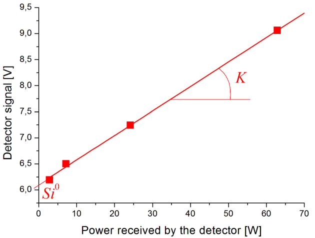
The thermographic device is calibrated with a black-body





Calibration curve according to the black-body temperature

- The calibration is carried out for each detectors,
- The signal evolution is non linear with the black -body temperature.

Calibration curve according to the power receive by the detector

- representation of the signal evolution according to the power receive by the detector

$$Si = Si^0 + K \int_0^{\lambda_c} \eta(\lambda) R_\lambda(T, \lambda) d\lambda,$$

- linear evolution,
- identification of the offset Si^0 and the gain K.

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Effect of emissivity on the temperature estimation

Error on the temperature due to emissivity

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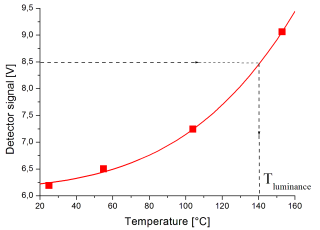
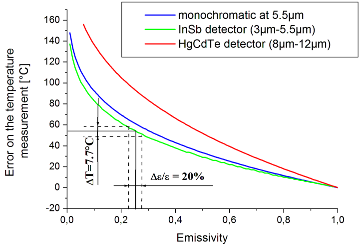
Luminance temperature

- The luminance temperature is the temperature measure by with the the surface is assumed to be a black-body surface.
- The emissivity of a surface is always lower than the unit : the luminance temperature is lower than the real temperature of the surface.



Error due to the emissivity

- The difference between the real and the luminance temperatures is 54.1 ℃ if the emissivity is 0.25. It is necessary to have an estimation of the emissivity,
- Estimation of emissivity with an uncertainty of 20% : the error on temperature is 7.5 ℃ which correspond to a relative error of 2%.



Measurement of the surface emissivity

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Experimental device to measure emissivity

- Enclosure at ambient temperature : measure of an apparent emissivity

$$\varepsilon_{app} = \varepsilon + (1 - \varepsilon)\frac{R^0_\lambda(T_{amb}, \lambda_{max})}{R^0_\lambda(T, \lambda_{max})}$$

- One half of the specimen is covered by a black paint : the measure is made by comparison of signal with and with out black paint

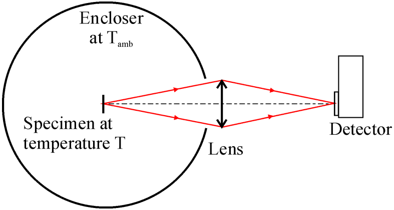

FIGURE : Experimental device for emissivity measurement.

Estimation of emissivity of the deformed surface

- Effect of roughness and temperature on emissivity :

$$\varepsilon = 0,25 \pm 0,025$$

- Error on temperature : 2% ($\approx$ 7 ℃)

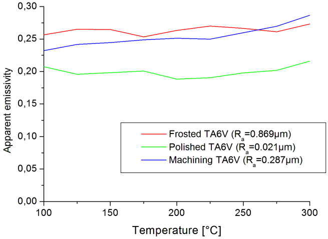

FIGURE : Evolution of emissivity of the surface.

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Temperature measurement inside an ASB

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Low temperature device : 50 ℃-300 ℃

- Spectral range : 1 µm - 5.5 µm,
- Space resolution : 43 µm (32 measurement points) ,
- Sampling frequency : 1 MHz,
- Variation range of emissivity : $\varepsilon = 0,25 \pm 0,025$,
- Error on the temperature : 2%.

High temperature device : 800 ℃ - 1600 ℃

- Spectral range : 0.4 µm-0.8 µm (high thermal sensitivity, minimisation of the emissivity effect),
- Space resolution : 2 µm (2D measurement),
- Only one image (1024x1024 pixels),
- Aperture time : 10 µs,
- Error on the temperature measurement : 6%.

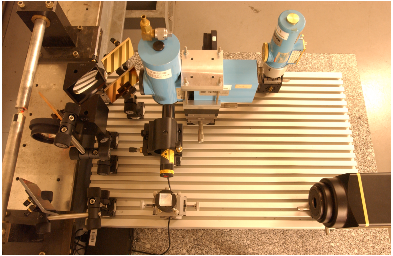
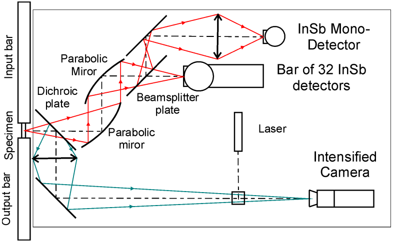


FIGURE : Temperature measurement device



Specimen and measurement positions

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Torsion specimen

- material : titanium alloy TA6V,
- tubular specimen,
- dynamic torsion loading with a strain rate of $\approx 1000\,s^{-1}$.

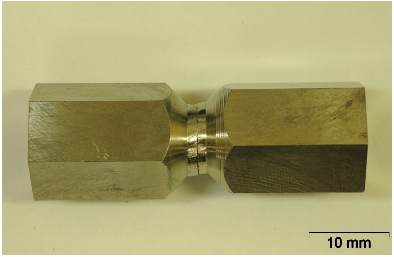


FIGURE : Torsion specimen

Localization of the measurement positions

- 32 mesurement points located along the specimen axis
- the size of the mesurement zone is 43 µmand the distance between two detectors is 18 µm

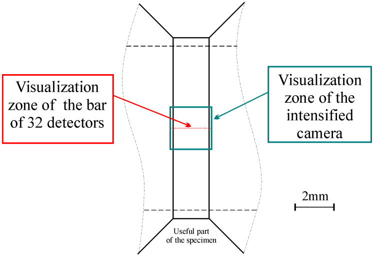
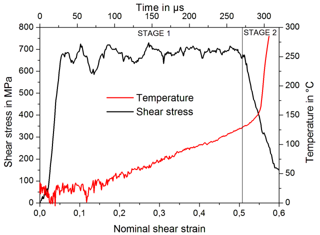
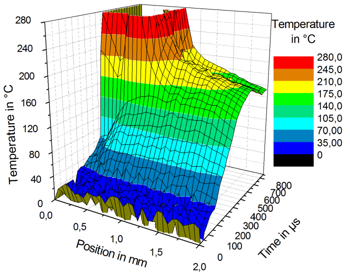


FIGURE : Localization of the measurement positions

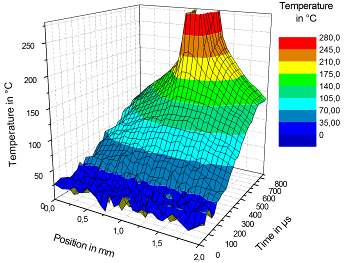
Experimental results





Experimental results

- Stage 1 : homogeneous temperature field,
- Stage 2 : heterogeneous temperature field ; stress drop,
- at the initiation stage one or two bands can be observed.



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Conclusions

- The used of IR thermography in high speed loading is possible but more difficult because of :
  - time resolution,
  - low radiated power,
  - choice of the shorter wavelength,
  - necessity to take into account of the emissivity.

Thanks for your attention

Any questions ?

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