High speed and high spatial resolution pyrometry – application to adiabatic shear band in titanium alloy

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Dynamic loading: application to the armour perforation

- Perforation of an armour in steel by a kinetic projectile
  Projectile velocity: $\approx 1500 \text{m/s}$

To design materials less sensitive to adiabatic shearing
$\Rightarrow$ Improvement of the armour protection
Adiabatic shear band phenomenon

Initiation mechanism proposed by Zener et Hollomon (1944)

- High strain rate loading
- Plastic strain: mechanical energy dissipated into heat
- Low thermal diffusion in the material (adiabatic phenomenon)
- Local increase in the temperature
- Thermal softening of the materials (decrease in the yield stress with the increase in the temperature)
- Catastrophic mechanism which produce a localization of the plastic strain in the form of fine shear bands (ASB)

Characteristics of these ASB: band width 10µm;
Formation duration of few ten microseconds
Study of adiabatic shearing

• Objective: understand the initiation and propagation mechanisms of ASB
  
  Temperature measurements in the ASB
  ⇒ Choice of the measurement technique by pyrometry (nonintrusive, fast...)

• Choice of two ranges of temperatures:
  
  • "Low temperature" 50°C – 300°C; study of band initiation; size of measurement: 50µm, integration time: 1µs, acquisition frequency: 1 MHz and 32 points of measurement
  
  • "High temperature" 800°C – 1600°C; estimation of the maximum temperature in the band: size of measurement: 2µm, integration time: 10µs; one thermography of 1024x1024 pixels
Plan of the presentation

• Pyrometry: theoretical aspects
• Choice of detectors
  – Maximum of emitted power
  – Maximum of sensibility: low wavelength pyrometry
  – Thermal fluctuation
  – Noise of detectors
• Calibration and emissivity
  – Calibration with a blackbody
  – Effect of emissivity, emissivity measurement
• Measurement device associated with adiabatic shear band study
• Results and conclusion
The radiation emitted by the surface of the specimen (spectral intensity $I_\lambda$) depend on its temperature and the wavelength:

Planck law: 

$$I_\lambda = \varepsilon(\lambda, T) \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

$\varepsilon(\lambda, T)$: emissivity $\in [0;1]$ (thermo-optical characteristic of the surface)

$\varepsilon = 1$: blackbody case

Design of a pyrometer:
- design of the optical device
- Choice of a detector
Choice of the detector
Spectral intensity of a blackbody: maximum of energy

- **Blackbody**: Spectral intensity given by the Planck’s law:
  \[ I_\lambda = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right)-1} \]

- **Maximum of emitted energy**: Wien’s law
  \[ \lambda_{\text{max}} = \frac{2900}{T} \]

- **Examples**:
  - 77K : \( \lambda_{\text{max}} = 38\mu m \)
  - 200°C : \( \lambda_{\text{max}} = 6\mu m \)
  - 1000°C : \( \lambda_{\text{max}} = 2\mu m \)
  - 1600°C : \( \lambda_{\text{max}} = 1\mu m \)
Detectors used in fast pyrometry

The quantum detectors and their spectral sensitivity:

- **Photoemissive detectors**: (bi-alcali, multi-alcali, AsGa: $\lambda_c=0.8\mu$m)
  - Photomultiplier
  - Intensified CCD Camera

- **Photovoltaic or photoconductor detectors**: (InSb $\lambda_c=5.5\mu$m; HgCdTe $\lambda_c=12\mu$m)
  - Semiconductors
  - Infrared CCD Camera

![Spectral sensitivity diagram](image-url)
Sensibility of the spectral intensity of the blackbody to a temperature variation

\( \lambda = 2,3\mu m \); \( T = 1000°C \)
(Maximum of spectral intensity)

Sensibility to a variation of 1°C:

\[
\frac{\Delta L_0^\lambda}{L_0^\lambda} = 0,4\%
\]

\( \lambda = 0,8\mu m \); \( T = 1000°C \)
("short" wavelength)

Sensibility to a variation of 1°C:

\[
\frac{\Delta L_0^\lambda}{L_0^\lambda} = 1,0\%
\]

\( \Rightarrow \) Sensibility almost 3 times higher

Choice of the shortest possible wavelength
Wavelength and detector choices

• **Choice of the shortest possible wavelength:**
  ⇒ The detector must be able to detect the emitted signal:
  • the signal to noise ratio must be sufficient
  • for short wavelength, the signal corresponds to a sufficient number of photon?
  • The randomness of the emission does not generate it additional noise and errors? (fluctuations)
Fluctuations of the black body intensity for short wavelength

- The photon emission is a random phenomenon
  (This randomness is all the more significant since the number of emitted photon is small)
- The spectral intensity given by the Planck’s law is a mean value:
  \[ I_\lambda^0 = \frac{1}{\Delta t} \int_t^{t+\Delta t} i_\lambda^0 (t) dt \]
- Root mean square (white noise):
  \[ (\delta i_\lambda^0)^2 = \frac{1}{\Delta t} \int_t^{t+\Delta t} (i_\lambda^0 (t) - I_\lambda^0)^2 dt \]
  \[ (\delta i_\lambda^0)^2 = kT^2 \frac{\partial I_\lambda^0}{\partial T} \]
Fluctuations: effect on the temperature measurement for the “high temperatures”

Increase in the relative fluctuation when the temperature and the photon number decrease

For $\lambda = 0.8\mu m$, the fluctuations become negligible for temperatures higher than 900°C

$\Rightarrow$ choice of an intensified camera AsGa for the "high temperatures"
Choice of the detector for the low temperatures ($\approx 200^\circ C$)

- Choice between the band II ($3\mu m - 5\mu m, InSb$) and the band III ($8\mu m - 12\mu m, HgCdTe$)

Better signal to noise ratio

$\text{InSb} : D^* = 8.97 \times 10^{10} \text{ W}^{-1} \text{cmHz}^{1/2}$

$\text{HgCdTe} : D^* = 2.89 \times 10^{10} \text{ W}^{-1} \text{cmHz}^{1/2}$

(detector surface: $1\text{cm}^2$, aperture: $180^\circ$, electronic band width: $1\text{Hz}$, background temperature: $293K$)

$\Rightarrow$ Choice of a InSb detector for the “low temperatures”
Choice of the detector for the low temperatures ($\approx 200^\circ C$)

- variation of signal associated with a temperature increase of 1°C to the noise ratio:

![Graph showing signal variation to noise ratio vs temperature for InSb and HgCdTe detectors.](image)

- Surface Detector surface: 43µm x 43µm, magnification: 1, detector aperture: 0.785sr (60°), optical aperture: 0.121sr, electronic band width: 1MHz

⇒ Choice of an InSb detector for the “low temperatures”
Calibration – Measurement of emissivity
Calibration on a blackbody
Case of the “low temperatures”

\[ Si = S_i^\circ + k \mathcal{P}(T) \]

Identification of \( S_i^\circ \) and \( k \)

Calibration curve of one InSb detector
Calibration on a blackbody
Case of the “high temperatures”

\[ Si = Si^\circ + k \mathcal{P}(T) \]

Identification of \( Si^\circ \) and \( k \)

Calibration curve
(mean value on around 10000 pixels)
Error on the temperature due to emissivity

Balckbody assumption $\varepsilon(\lambda, T) = 1$ : luminance temperature

For $T = 1000^\circ C$ (High temperatures):

- intensified camera ($0.4\mu m - 0.8\mu m$), coarse estimate of $\varepsilon$ at 0,40 with $\Delta\varepsilon/\varepsilon = 100\%$ : error on the temperature: $86^\circ C$ (7%)
- InSb detector ($4.5\mu m$), coarse estimate of $\varepsilon$ at 0,25 with $\Delta\varepsilon/\varepsilon = 100\%$ : error on the temperature: $313^\circ C$ (25%)

For $T = 200^\circ C$ (Low temperatures):

- InSb detector ($4.5\mu m$), coarse estimate of $\varepsilon$ at 0,25 with $\Delta\varepsilon/\varepsilon = 100\%$ : error on the temperature: $158^\circ C$ (33%)
- InSb detector ($4.5\mu m$), measure of $\varepsilon$ at $0.250\pm0.025$ ($\Delta\varepsilon/\varepsilon = 20\%$) : error: $9^\circ C$ (1,6%)

⇒ Need to measure emissivity for the “low temperatures”
Measurement of the surface emissivity in the IR domain

- Device of emissivity measurement

- Emissivity for various surface roughness according to the temperature

\[ \varepsilon = 0.250 \pm 0.025 \]
Device associated with adiabatic shear band study
Torsional Hopkinson bars

Hydraulic engine
Brake
Specimen
Output bar
Input bar

Hydraulic engine
Brake
Torsion specimen
Bearing

Strain gage
Input bar
Output bar
Strain gage
Temperature measurement device

"Low temperature" device (20°C to 300°C):
- wavelength: 1 à 5.5 µm
- spatial resolution: 43 µm
- temporal resolution: 1 µs

"High temperature" device (600°C to 1500°C):
- wavelength: 0.4 to 0.8 µm
- spatial resolution: 5 µm
- temporal resolution: 10 µs

Trigger device
Torsion specimen

Specimen after ASB formation

Visualization zones of the bar of detectors and the intensified camera on the specimen
Results
Results: low temperature

PHASE 1: homogeneous temperature field

PHASE 2: decrease of the stress, heterogeneous temperature field
Results: high temperature

Aperture time 10µs; $T_{\text{max}} \approx 1000^\circ\text{C}$

temperature heterogeneity in the ASB
Conclusion

• **Study of adiabatic shearing**
  – High speed and very localised phenomenon

• **Choice of the adapted detector**
  – Higher sensibility: shortest possible wavelength
  – to check if the emitted signal is not too weak (fluctuations, signal to noise ratio)

• **Case of visible pyrometry**: possibility to measure simultaneously a displacement and a temperature fields with the same camera and the same optical device