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► **To cite this version:**

Vincent Delobelle, Denis Favier, Hervé Louche, Nathanael Connesson. Determination of Local Thermophysical Properties and Heat of Transition from Thermal Fields Measurement During Drop Calorimetric Experiment. *Experimental Mechanics*, 2015, 55 (4), pp.711-723. 10.1007/s11340-014-9877-z . hal-01300519

HAL Id: hal-01300519

<https://hal.science/hal-01300519v1>

Submitted on 11 Apr 2016

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Determination of local thermophysical properties and heat of transition from thermal fields measurement during drop calorimetric experiment

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Abstract

This paper proposes a non-contact original method to estimate local thermophysical properties (heat capacity and thermal conductivity) and heats of transition from plane thin specimens. This method is based on measurement of temperature fields with an infrared camera during a drop calorimetric experiment. A studied specimen and a reference specimen, with similar geometries, are simultaneously tested. Firstly, the method is validated by estimating heat capacity and thermal conductivity of Vanadium specimens and by comparing the determined values with those obtained by Differential Scanning Calorimetry and by a laser flash method, respectively. Secondly, the method is used to determine latent heats of martensitic transformations. These heats of transition are determined during homogeneous and heterogeneous drop calorimetric experiments of NiTi shape memory alloys specimens. Measured transformation temperatures and latent heats are in good accor-

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dance with results obtained by Differential Scanning Calorimetry.

Key words: Infrared thermography, heat capacity, thermal conductivity, heat sources estimation, experimental benchmark, NiTi Shape Memory Alloy

1. Introduction

Knowledge of heat capacity and thermal conductivity of materials is of crucial importance to model heat exchanges in materials. Heat capacity of materials can be measured with adiabatic calorimeter, Differential Scanning Calorimetry (DSC) [1], modulated DSC [2, 3], dynamic DSC [4], etc. Materials thermal conductivity is generally measured using a hot wire method [5], the derived hot strip method, a laser flash method [6] or a 3ω method [7]. Heat of transition is generally measured by DSC [8] or Differential Thermal Analysis. All these classical techniques allow a global measurement of the desired property at the specimen scale. However, in some cases, a local measurement of these properties would be useful, for example in the case of heterogeneous specimens [9] or graded material [10, 11]. The method proposed in this paper allows to locally estimate heat capacity, thermal conductivity and heat of transition from a thin plate specimen. The method has been validated in this paper for homogeneous specimen although it could also be applied to heterogeneous specimen. In such a case, a field of heat capacity, thermal conductivity and heat of transition could be determined.

Infrared measurements are increasingly used. In order to estimate temperature fields on the specimens surface, emissivity property is classically controlled using high emissivity paint on the specimen surface. Heat sources

21 estimations based on these temperature fields were proposed in [12, 13].
22 These estimations were used to study several mechanical coupled problems
23 such as Lüders bands and necking in steels [12, 14], fatigue of materials
24 [15, 16, 17, 18], plasticity in Al oligocrystal [19], thermomechanical behaviour
25 of NiTi Shape Memory Alloys (SMA) [13, 20, 21, 22, 23], *etc.*

26 In this paper, an original method, called Thermal Field Measurement
27 (TFM) method, is proposed. This non-contact method allows to estimate
28 thermophysical properties of material and heat of transition locally while
29 classical methods are global. This method is based on the observation with
30 an infrared camera of the natural cooling of two specimens (one being the
31 'reference' while the other is 'studied').

32 In the first section, the TFM models and method are presented. Heat dif-
33 fusion models, method principle, and the methods to estimate heat capacity,
34 thermal conductivity and heat of transition are successively proposed.

35 The second section is an experimental validation. First, experimental
36 setup, materials and data processing are presented. Then, heat capacity
37 of Vanadium C_{Va} was estimated using TFM method and DSC. Results are
38 successfully compared. Then, Vanadium thermal conductivity k_{Va} was esti-
39 mated using TFM method. Results are compared to those obtained with the
40 laser flash method. Finally, heat of transition of NiTi SMAs was estimated
41 in a homogeneous and heterogeneous case with the TFM method. Results
42 are successfully compared to those obtained by DSC, which is the standard
43 method to determine characteristic temperatures and heat of the martensitic
44 transformations occurring in this material [24].

45 2. Thermal Field Measurement Models and Methods

46 2.1. Heat diffusion models

47 In this part, the heat diffusion models used in the following are presented.
48 The general 3D heat diffusion equation linking temperature $T(x, y, z, t)$ and
49 heat sources $s(x, y, z, t)$ at a spatial point located in (x, y, z) at current time
50 t , is expressed in the following form:

$$\rho C \frac{\partial T}{\partial t} - k \text{lap}(T) = s = \rho \dot{q}, \quad (1)$$

51 where ρ is the mass density, C the heat capacity, k the thermal conduc-
52 tivity of the material and lap stands for the laplacian operator. In the right
53 hand side of this equation, s is the volumic heat sources ($W m^{-3}$) and $\dot{q} = \frac{s}{\rho}$
54 represents the massic heat sources in the material ($W kg^{-1}$).

55 Figure 1 shows the specimens used in the present paper. The two sides of
56 the sample (1) of thickness e_1 are coated with a high emissivity paint (p) of
57 thickness e_P . The properties of the material or paint are the mass density ρ_i ,
58 thermal conductivity k_i , heat capacity C_i and volumic heat sources s_i where
59 i indexes the material ($i = 1$) or the paint ($i = p$). The two paint layers are
60 supposed identical (properties and thickness).

61 In order to take into account the two paint layers presented in Fig. 1, the
62 plate is considered as a sandwich material. Mathematical developments to
63 write models presented below are fully explained in [12, 13] in the case of an
64 homogeneous plate in the thickness. Identical development can be done in
65 the case of a sandwich material, as explained in [33, 35].

66 A first model is obtained for thin plane sandwich specimen. Integrating
67 equation 1 in the specimen thickness (z in Figure 1) provides the following

68 2D model:

$$\frac{2e_p\rho_p C_p + e_1\rho_1 C_1}{e_1} \frac{\partial \tilde{T}}{\partial t} - \frac{2e_p k_p + e_1 k_1}{e_1} \text{lap}_{2D}(\tilde{T}) + \frac{f}{e_1} = \tilde{s}_1, \quad (2)$$

69 where $\tilde{T} = \tilde{T}(x, y, t)$ is the averaged temperature in the thickness of the
70 specimen and $\text{lap}_{2D}(\tilde{T}) = \frac{\partial^2 \tilde{T}}{\partial x^2} + \frac{\partial^2 \tilde{T}}{\partial y^2}$. In equation 2, \tilde{s}_1 represents the volumic
71 heat sources ($W m^{-3}$) in the specimen. Heat sources in the paint are sup-
72 posed null ($s_p=0$). The function f models heat losses from the lateral surfaces
73 by radiation f_{rad} and convection f_{conv} , leading to the following expression:

$$f(x, y, \tilde{T}) = \underbrace{2\epsilon\sigma(\tilde{T}^4 - T_0^4)}_{f_{rad}} + \underbrace{2h(\tilde{T} - T_0)}_{f_{conv}}, \quad (3)$$

74 where T_0 is the ambient temperature, ϵ the paint layer emissivity, σ the
75 Stephan-Boltzman constant, and h is the convection coefficient. As shown
76 in equation 3, this function $f(x, y, \tilde{T})$ is independent on the material. A
77 second model can be obtained to study the case of uniaxial heterogeneous
78 thermal field, for exemple for slender thin plane specimen. Assuming a quasi-
79 homogeneous field in the transverse direction, equation 2 can be integrated in
80 the transverse direction (y in Figure 1) which allows to write the 1D model:

$$\frac{2e_p\rho_p C_p + e_1\rho_1 C_1}{e_1} \frac{\partial \tilde{\tilde{T}}}{\partial t} - \frac{2e_p k_p + e_1 k_1}{e_1} \text{lap}_{1D}(\tilde{\tilde{T}}) + \frac{f}{e_1} = \tilde{\tilde{s}}_1, \quad (4)$$

81 where $\tilde{\tilde{T}} = \tilde{\tilde{T}}(x, t)$ is the average of \tilde{T} in the transverse direction of the
82 specimen and $\text{lap}_{1D}(\tilde{\tilde{T}}) = \frac{\partial^2 \tilde{\tilde{T}}}{\partial x^2}$. In that case the heat losses function is written:

$$f(x, \tilde{\tilde{T}}) = \underbrace{2\epsilon\sigma(\tilde{\tilde{T}}^4 - T_0^4)}_{f_{rad}} + \underbrace{2h(\tilde{\tilde{T}} - T_0)}_{f_{conv}}, \quad (5)$$

83 Finally, a third model can be obtained in the case of uniform temperature.
 84 Integrating equation 4 in the axial direction provides the 0D model:

$$\frac{2e_p\rho_pC_p + e_1\rho_1C_1}{e_1} \frac{d\tilde{\tilde{T}}}{dt} + \frac{f}{e_1} = \tilde{\tilde{s}}_1, \quad (6)$$

85 where $\tilde{\tilde{T}} = \tilde{\tilde{T}}(t)$ is the temperature average of $T(x, y, z, t)$. The heat losses
 86 function is written:

$$f(\tilde{\tilde{T}}) = \underbrace{2\epsilon\sigma(\tilde{\tilde{T}}^4 - T_0^4)}_{f_{rad}} + \underbrace{2h(\tilde{\tilde{T}} - T_0)}_{f_{conv}}. \quad (7)$$

87 These 2D, 1D and 0D model will be used to analyze the temperature
 88 fields variation versus time during different drop calorimetric experiments.

89 2.2. TFM Method principle

90 All the experiments are based on the observation of the simultaneous
 91 natural cooling in the same environment of two specimens, referred to as
 92 'studied' (s) and 'reference' (r) specimen (Figure 2). The thermal capacity
 93 and conductivity of the 'reference' specimen are known. Furthermore, no
 94 transformation within the 'reference' specimen occurs in the temperature
 95 range ($\tilde{s}_1 = \tilde{\tilde{s}}_1 = \tilde{\tilde{\tilde{s}}}_1 = 0$).

96 During the experiments, the 'studied' and 'reference' specimens are lo-
 97 cated in the same thermal environment. The two specimens are painted with
 98 an identical high emissivity paint ($\epsilon_r = \epsilon_s = \epsilon$). Thus:

- 99 • The radiation part f_{rad} of the heat losses function f is identical for
 100 both specimens and is only function of the temperature (equations (3),
 101 (5) and (7)).

102 • The second part of the heat losses function f_{conv} is due to convection.
103 The heat transfer coefficient h is dependent on the heat transfer mode,
104 the flow regime, etc: the heat transfer coefficient h may depend on the
105 local convection mode:

106 • First, in the homogeneous case (equation (7)), h is only function of $\tilde{\tilde{T}}$,
107 i.e. $h(\tilde{\tilde{T}})$.

108 • Second, in the 1D case (equation (5)), h is only function of $\tilde{\tilde{T}}$ and x ,
109 i.e. $h(\tilde{\tilde{T}}, x)$.

110 • Last in the 2D case (equation (3)), h is function of $\tilde{\tilde{T}}$, x , and y , i.e.
111 $h(\tilde{\tilde{T}}, x, y)$.

112 The 'studied' and 'reference' specimens being in the same environment,
113 the heat losses functions (3), (5) and (7) are assumed identical for the two
114 specimens.

115 For the 'reference' specimen, heat sources are zero during all the experi-
116 ments. Thus this specimen is used to estimate the local heat losses function f
117 from equations (2), (4) and (6) applied to the 'reference' thermal fields mea-
118 sured during the drop calorimetric experiment. Then, the local heat losses
119 function f is used in different configurations to estimate the local heat ca-
120 pacity (section 2.3), thermal conductivity (section 2.4) and heat of transition
121 (section 2.5) of the 'studied' specimen.

122 2.3. Estimation of heat capacity C for homogeneous samples

123 For homogeneous sample, estimation of heat capacity C is performed
124 while observing simultaneous uniform temperature cooling of the studied

125 and reference specimens (Figure 2.a). During the experiment, the specimen
 126 surface temperature fields T_s and T_r of 'studied' and 'reference' specimens, re-
 127 spectively, are measured and the temperature field homogeneities are checked
 128 experimentally. The materials and experimental temperature range are cho-
 129 sen so that no phase change occurs in the materials during the experiment;
 130 heat sources s are zero. Thus, the 0D thermal model (equation (6)) applied
 131 to each of the two specimens provides the equations:

$$(\rho_s C_s e_s + 2\rho_p C_p e_p) \frac{d\tilde{\tilde{T}}_s}{dt} = -f(\tilde{\tilde{T}}_s), \quad (8)$$

$$(\rho_r C_r e_r + 2\rho_p C_p e_p) \frac{d\tilde{\tilde{T}}_r}{dt} = -f(\tilde{\tilde{T}}_r). \quad (9)$$

132 The reference thermophysical properties being known and $\tilde{\tilde{T}}_r$ being mea-
 133 sured, $f(\tilde{\tilde{T}})$ can be computed using equation (9) and the estimation of $\frac{\partial \tilde{\tilde{T}}_r}{\partial t}$
 134 from experimental cooling curve of the reference specimen.

135 Furthermore, when $\tilde{\tilde{T}}_s = \tilde{\tilde{T}}_r = \tilde{\tilde{T}}$, the heat losses function $f(\tilde{\tilde{T}})$ is identical
 136 for both 'reference' and 'studied' specimens and the studied specimen heat
 137 capacity C_s can be computed by:

$$C_s(\tilde{\tilde{T}}_s) = \frac{f(\tilde{\tilde{T}}_s) - 2\rho_p C_p e_p \frac{d\tilde{\tilde{T}}_s}{dt}}{\rho_s e_s \frac{d\tilde{\tilde{T}}_s}{dt}}. \quad (10)$$

138 All the thermo-physical properties in the right hand side of equation 10
 139 are known. The term $\frac{d\tilde{\tilde{T}}_s}{dt}$ is estimated at temperature $\tilde{\tilde{T}}_s$ from the experi-
 140 mental cooling curve of the studied specimen.

141 *2.4. Estimation of thermal conductivity k*

142 Using the experimental setup proposed in Figure 2.b, axially heteroge-
 143 neous (1D) temperature fields are obtained during cooling and are used to
 144 estimate the thermal conductivity k . Once again for that experiment, the
 145 material and temperature range are chosen so that no transition occurs dur-
 146 ing the experiment; so heat sources are zero. Applying equation (4) to each
 147 of the two specimens, and considering hypotheses previously described, it
 148 can be written:

$$(\rho_s C_s e_s + 2\rho_p C_p e_p) \frac{\partial \tilde{T}_s}{\partial t} - (k_s e_s + 2k_p e_p) \frac{\partial^2 \tilde{T}_s}{\partial x^2} = -f(x_s, \tilde{T}_s), \quad (11)$$

$$(\rho_r C_r e_r + 2\rho_p C_p e_p) \frac{\partial \tilde{T}_r}{\partial t} - (k_r e_r + 2k_p e_p) \frac{\partial^2 \tilde{T}_r}{\partial x^2} = -f(x_r, \tilde{T}_r). \quad (12)$$

149 In these equations, only f and k_s are unknown. $f(x, \tilde{T})$ can be estimated
 150 thanks to equation 12 and the experimental data for the reference specimen.
 151 From these data, the terms $\frac{\partial \tilde{T}_r}{\partial t}$ and $\frac{\partial^2 \tilde{T}_r}{\partial x^2}$ are estimated for every position x
 152 and temperature T . At the position $x_s = x_r = x$ from the mass, and at the
 153 temperature $\tilde{T}_s = \tilde{T}_r = \tilde{T}$, the studied specimen thermal conductivity k_s can
 154 thus be determined:

$$k_s(x_s, \tilde{T}_s) = \frac{f(x_s, \tilde{T}_s) + (\rho_s C_s e_s + 2\rho_p C_p e_p) \frac{\partial \tilde{T}_s}{\partial t} - 2k_p e_p \frac{\partial^2 \tilde{T}_s}{\partial x^2}}{e_s \frac{\partial^2 \tilde{T}_s}{\partial x^2}}. \quad (13)$$

155 The term $\frac{\partial \tilde{T}_s}{\partial t}$ is estimated for every position from the 'studied' specimen
 156 cooling curves and the term $\frac{\partial^2 \tilde{T}_s}{\partial x^2}$ is estimated for every temperature from

157 the 'studied' specimen thermal profiles. All the thermo-physical properties
 158 in the right hand side of equation 13 are known.

159 *2.5. Estimation of local heat of transition*

160 The reference and studied materials and temperature range are chosen in
 161 this experiment so that:

- 162 • no phase change occurs in the 'reference' specimen,
- 163 • phase change occurs in the 'studied' specimen.

164 Heat of transition is estimated using the experimental set-up proposed in
 165 Figure 2.a (homogeneous cooling) or Figure 2.b (heterogeneous 1D cooling).

166 *2.5.1. Homogeneous (0D) cooling*

167 Homogeneous (0D) temperature fields are obtained during cooling. Equa-
 168 tion 6 applied to the 'studied' and 'reference' specimens provides two equa-
 169 tions:

$$\frac{(\rho_s C_s e_s + 2\rho_P C_P e_P) d\tilde{\tilde{T}}_s}{e_s} = \rho_s \tilde{\tilde{q}}_s - f(\tilde{\tilde{T}}_s), \quad (14)$$

$$(\rho_r C_r e_r + 2\rho_P C_P e_P) \frac{d\tilde{\tilde{T}}_r}{dt} = -f(\tilde{\tilde{T}}_r). \quad (15)$$

170 Again, the heat losses function $f(\tilde{\tilde{T}})$ is identical for 'reference' and 'stud-
 171 ied' specimens. $f(\tilde{\tilde{T}})$ is estimated from equation 15.

172 Thus, at the temperature $\tilde{\tilde{T}}_s$, the studied specimen heat source can be
 173 computed by:

$$\tilde{\tilde{q}}_s(\tilde{\tilde{T}}_s) = \frac{(\rho_s C_s e_s + 2\rho_P C_P e_P)}{e_s \rho_s} \frac{\partial \tilde{\tilde{T}}_s}{\partial t} + \frac{f(\tilde{\tilde{T}}_s)}{e_s \rho_s}. \quad (16)$$

174 *2.5.2. Axially heterogeneous (1D) cooling*

175 Using the experimental setup proposed in Figure 2.b, heterogeneous (1D)
 176 temperature fields are obtained. In that case equation 4 applied to each of
 177 the two specimens provides two equations:

$$\frac{(\rho_s C_s e_s + 2\rho_P C_P e_P)}{e_s} \frac{\partial \tilde{\tilde{T}}_s}{\partial t} - \frac{(k_s e_s + 2k_P e_P)}{e_s} \frac{\partial^2 \tilde{\tilde{T}}_s}{\partial x^2} = \rho_s \tilde{\tilde{q}}_s - \frac{f(x_s, \tilde{\tilde{T}}_s)}{e_s}, \quad (17)$$

$$(\rho_r C_r e_r + 2\rho_P C_P e_P) \frac{\partial \tilde{\tilde{T}}_r}{\partial t} - (k_r e_r + 2k_P e_P) \frac{\partial^2 \tilde{\tilde{T}}_r}{\partial x^2} = -f(x_r, \tilde{\tilde{T}}_r). \quad (18)$$

178 Equation 18 and experimental data for the reference specimen is used
 179 to estimate $f(x, \tilde{\tilde{T}})$. At the temperature $T = T_s = T_r$ and at the position
 180 $x = x_s = x_r$, heat sources released by the 'studied' material are:

$$\tilde{\tilde{q}}_s(x_s, \tilde{\tilde{T}}_s) = \underbrace{\frac{(\rho_s C_s e_s + 2\rho_P C_P e_P)}{e_s \rho_s} \frac{\partial \tilde{\tilde{T}}_s}{\partial t}}_{\text{Heat storage term}} - \underbrace{\frac{(k_s e_s + 2k_P e_P)}{e_s \rho_s} \frac{\partial^2 \tilde{\tilde{T}}_s}{\partial x^2}}_{\text{Conduction term}} + \underbrace{\frac{f(x_s, \tilde{\tilde{T}}_s)}{e_s \rho_s}}_{\text{Heat losses term}}. \quad (19)$$

181 This experiment would be useful for heterogeneous specimen and would
 182 allow to determine local heat of transition.

183 3. Experimental validation

184 3.1. Experimental setup

185 In this study a SC7600 (Flir) camera was used. The camera works in
186 the IR wavelength $\lambda = 3 - 5 \mu m$ with an InSb detector matrix (15×15
187 μm^2) and a resolution of 640×480 pixels. The accuracy of the camera is
188 $\pm 2^\circ C$ in the concerned temperature range and its thermal resolution is about
189 $0,02^\circ C$. The frame rate was 25 Hz. The industrial camera calibration has
190 been performed with a black body in the range -10 to $300^\circ C$.

191 All specimens were painted with high emissivity paint measured to be
192 $\epsilon = 0,95$. Paint thickness was measured with scanning electron microscope
193 to be $25 \pm 5 \mu m$. IR transmission through the specimen and reflection of
194 the environment, that can affect the measure, have been neglected.

195 Temperature measurements of the specimen located in the chamber were
196 performed through a quasi-transparent IR windows in CaF₂ (Figure 3). This
197 window offers a transmission coefficient of $\tau = 0,92$ in the used wavelength.
198 The two specimens were heated up to a known temperature T_{ini} using a first
199 hot climatic chamber before being carried into a second cold climatic chamber
200 controlled at a known temperature T_0 . To reduce cooling while carrying the
201 specimens between the two chambers, a specific device was used. The natural
202 cooling of the specimens in this second climatic chamber, from T_{ini} to T_0 , was
203 observed with the IR camera.

204 In order to obtain homogeneous (0D) or axially heterogeneous (1D) tem-
205 perature fields during cooling, two types of specimens and fixing were chosen
206 (Figure 3). In the first case, small specimens were suspended with thin ther-
207 mal insulator wires in order to obtain uniform temperature in each specimen

208 (Figure 3.a). In the second case, slender specimens were used and gripped in
209 a steel block, acting as a thermal mass. This thermal mass initially at tem-
210 perature T_0 cooled very slowly and created an axial temperature gradient
211 between the free and gripped extremities in each specimen (Figure 3.b).

212 Reproducibility and heat losses distributions in time and space were
213 tested. Experiments were realized using for the reference and studied spec-
214 imens two identical specimens with the same material. In such a case, re-
215 sponses of the two specimens were measured to be identical in the whole
216 range of temperature.

217 3.2. Materials

218 As explained in the first section, a 'reference' specimen is used to evaluate
219 heat losses functions in equations (9),(12),(15), (18). Pure Titanium, in
220 the form of 0.51 mm thickness sheet, was selected in our experiments as
221 'reference' specimen. The thermophysical properties of this material are
222 given in Table 1 as reported in the literature. They were also measured using
223 classical methods. Its heat capacity was measured with a DSC experiment
224 and was estimated to $C_{Ti}^{DSC} = 530 \pm 30 \text{ Jg}^{-1}\text{K}^{-1}$. This result is in good
225 agreement with the literature values (Table 1). In the following, a value of
226 $C_{Ti} = 530 \text{ Jg}^{-1}\text{K}^{-1}$ has been used. The thermal diffusivity ($\lambda = \frac{k}{\rho C}$) of
227 this Titanium specimen was estimated using a laser flash method [33, 36,
228 37]. Knowing the heat capacity of the material, the thermal conductivity of
229 Titanium was estimated to $k_{Ti}^{lf} = 20 \pm 2 \text{ Wm}^{-1}\text{K}^{-1}$. This result is in good
230 agreement with the values of the literature (Table 1). In the following, a
231 value of $k_{Ti} = 20 \text{ Wm}^{-1}\text{K}^{-1}$ has been used.

232 The 'studied' specimens were cut either in pure Vanadium rolled plate

233 of thickness 0.50 mm (Sections 3.3 and 3.4) or in a Ti - 50.2 at.% Ni SMA
 234 bright rolled plate of thickness 0.39 mm (Section 3.5). The thermophysical
 235 properties of these materials and of the high emissivity paint are given in
 236 Table 1 as reported in the literature.

Material	Volumic mass ρ ($kg\ m^{-3}$)	Specific heat C ($J\ kg^{-1}\ K^{-1}$)	Thermal conductivity k ($W\ m^{-1}\ K^{-1}$)
Ti [25, 26, 27, 28, 29]	4510	520 - 555	17 - 22
Va [25, 26, 27, 30]	6000	480 - 505	28 - 36
NiTi [31, 32, 33]	6400	480 - 520	9 - 15
Paint [34]	1500	1500	0.2

Table 1: Thermophysical properties of used materials (literature values).

237 Figure 4 shows the DSC of the NiTi SMA selected for the study (section
 238 3.5). This DSC was performed using a DSC TA Q200, with a $10^{\circ}C\ min^{-1}$
 239 heating/cooling rate, with a specimen of 22.9 mg cut with a diamond blade.
 240 During cooling, two successive phase transformations were observed:

- 241 • from Austenite to R-phase, with $R_s = 62^{\circ}C$, $R_f = 53^{\circ}C$ the starting
 242 and finishing temperatures, respectively,
- 243 • from R-phase to Martensite, with $M_s = 39^{\circ}C$ and $M_f = 12^{\circ}C$ the
 244 starting and finishing temperatures, respectively.

245 The latent heat released during complete phase transformation, evaluated
 246 from the baseline plotted in Figure 4, is equal to $\Delta H_{A-M} = 21\ Jg^{-1}$. Dur-
 247 ing heating, a single phase transformation from Martensite to Austenite is

248 observed, with starting and finishing transformation temperatures equal to
249 $A_s = 69^\circ C$ and $A_f = 84^\circ C$, respectively.

250 3.3. Data processing

251 Temperatures $T_s(x, y, t)$ and $T_r(x, y, t)$ measured with the infrared camera
252 on the surface of the samples need to be processed to estimate the desired
253 properties (C , k or \dot{q}). The complete data processing flowchart performed
254 with Matlab is presented in Figure 5 for the 1D heterogeneous case.

255 In the 1D heterogeneous case, the temperature is supposed homogeneous
256 in the y direction. This assumption was experimentally checked. Thus, tem-
257 poral averaging in the y direction was estimated and data $\tilde{\tilde{T}}_s$ and $\tilde{\tilde{T}}_r$ were
258 obtained. Low pass temporal filtering was then applied to data as reported
259 in [12, 13]. Then, first derivative terms were estimated by finite difference
260 method and were spatially filtered. To estimate laplacian terms, data $\tilde{\tilde{T}}_s$ and
261 $\tilde{\tilde{T}}_r$ were spatially filtered with a polynomial of degree 4. Knowing the polyno-
262 mial coefficients, laplacian terms were estimated. This laplacian estimation
263 was studied and checked in [33]. Once the spatial and temporal derivative
264 terms estimated, the heat losses function f and desired property can be es-
265 timated using equations presented in section 2. A quasi similar flowchart
266 could be presented in the homogeneous case. Temperatures $T_s(x, y, t)$ and
267 $T_r(x, y, t)$ were averaged in x and y directions and only the derivative term
268 versus time was estimated.

269 3.4. Validation of the TFM heat capacity C measurement

270 In this section, the experimental setup proposed in Fig. 3.a and tem-
271 peratures $T_{ini} = 60^\circ C$ and $T_0 = 0^\circ C$ were chosen (Table 2). The reference

272 material was Titanium. The studied material was Vanadium.

Ref. Mat.	Studied Mat.	Exp. Setup	T_{ini}	T_0
Ti e = 0.51 mm	Va e = 0.50 mm	Fig. 3.a	60°C	0°C

Table 2: Information and parameters for TFM heat capacity measurement.

273 Figure 6.a shows the measured natural cooling curves of the Ti and Va
 274 specimens. Due to heat losses during the specimens transportation between
 275 the heat and cold chambers, the starting temperatures of the two specimens
 276 were slightly lower than temperature of the first chamber $T_{ini} = 60^\circ C$. Figure
 277 6.b shows the cooling rate of the two specimens in function of the specimen
 278 temperatures (estimated from the cooling curves). During that experiment,
 279 cooling rate decreases approximately linearly with the temperature.

280 Figure 7 shows the Vanadium heat capacity estimated with the TFM
 281 method for three experiments in the range 10 to 30°C using equation 10. This
 282 range was chosen because filtering process presented in section 3.3 involves
 283 edge effects on the estimation of the derivative terms. Moreover, below 10° C,
 284 the denominator of equation 10 is low and induces important noise. Results
 285 were obtained using the cooling rates ($\frac{dT}{dt}$) presented in Figure 6.b and a
 286 constant heat capacity $C_{Ti} = 530 Jkg^{-1}K^{-1}$.

287 A constant mean value $C_{Va}^{TFM} = 495 \pm 10 Jkg^{-1}K^{-1}$ was determined
 288 from these curves. As the C_{Ti} is known with an accuracy of $\pm 30 Jg^{-1}K^{-1}$
 289 from the DSC measurement, the Va heat capacity is finally estimated to
 290 be $C_{Va}^{TFM} = 495 \pm 40 Jkg^{-1}K^{-1}$ with the TFM method. This result is
 291 in good agreement with those obtained from DSC on the same material:

292 $C_{Va}^{DSC} = 480 \pm 40 \text{ Jkg}^{-1}\text{K}^{-1}$ and from literature $C_{Va}^{lit} = 480 - 505 \text{ Jkg}^{-1}\text{K}^{-1}$,
 293 obtained on different Va materials. The method proposed is thus considered
 294 experimentally validated. Heat capacity can be estimated with the same
 295 accuracy than the DSC method.

296 3.5. Validation of the TFM thermal conductivity k measurement

297 In this section, the used experimental setup is shown in the Figure 3.b and
 298 temperatures $T_{ini} = 60^\circ\text{C}$ and $T_0 = 0^\circ\text{C}$ were chosen (Table 3). Vanadium
 299 was used as the 'studied' material. Titanium was the 'reference' material.

Ref. Mat.	Studied Mat.	Exp. Setup	T_{ini}	T_0
Ti e = 0.51 mm	Va e = 0.50 mm	Fig. 3.b	60°C	0°C

Table 3: Information and parameters for TFM thermal conductivity measurement.

300 Figure 8 shows the thermal responses of Ti and Va specimens during the
 301 1D experiment. Figure 8.b is the spatio-temporal thermal response of the
 302 Ti specimen along the dashed line sketched in Figure 8.a. Figure 8.c shows
 303 the temperature temporal evolution of three pixels of Ti and Va specimens.
 304 Figure 8.d shows the axial thermal profiles sketched in Figure 8.a at different
 305 times for the Ti specimen. The specimens cooled during the experiment
 306 (Figures 8.b and c), from a quasi-homogeneous temperature to a thermally
 307 heterogeneous state with a gradient (Figures 8.b and d) in the specimen main
 308 direction. The Ti specimen cooled faster than the Va specimen, as during the
 309 0D experiment (Figure 8.c). Initial temperatures of the two specimens were
 310 almost equal (Figure 8.c). At the end of the experiment, the edge close to
 311 thermal mass was hotter than the free edge (Figure 8.d). As noted in Table

312 1, thermal conductivity of Titanium and Vanadium are different, leading to
 313 different heat flux through the specimens. This explains why, at the end of
 314 the experiment, the two specimens were not at room temperature T_0 and
 315 that the temperatures were different at a given distance of the thermal mass.

316 Figure 9 shows the estimated thermal conductivity of the Va specimen,
 317 using the equation (13). In this equation, the heat loss function $f(x, \tilde{T})$ was
 318 estimated from equation 12 and experimental data for the 'reference' spec-
 319 imen. Conductivity values are presented along the axial profile for instants
 320 higher than $t=30s$ in Figure 8.c. For those instants, first derivative terms
 321 $(\frac{\partial \tilde{T}}{\partial t})$ in equations 12 and 13 were negligible compared to the spatial second
 322 derivative $\frac{\partial^2 T}{\partial x^2}$. For the two samples, as observed on profiles presented in
 323 Fig. 8.d, laplacian term is higher close to steady state. To avoid important
 324 edges effect due to spatial filtering, only the central pixels were considered.
 325 Using $k_{Ti} = 20 \text{ Wm}^{-1}\text{K}^{-1}$, a mean thermal conductivity of Vanadium is
 326 estimated to be $k_{Va}^{TFM} = 37 \text{ Wm}^{-1}\text{K}^{-1}$. Note that this result is in good
 327 agreement with literature results (Table 1). Taking into account dispersion
 328 of Ti thermal conductivity, heat capacity, and Va heat capacity, Va thermal
 329 conductivity is estimated to be $k_{Va}^{TFM} = 36 \pm 4 \text{ Wm}^{-1}\text{K}^{-1}$ while it was es-
 330 timated to be $k_{Va}^{lf} = 34 \pm 3 \text{ Wm}^{-1}\text{K}^{-1}$ with a classical laser flash method
 331 and to be $k_{Va}^{lit} = 28 - 36 \text{ Wm}^{-1}\text{K}^{-1}$ in the literature. Thus, while esti-
 332 mating thermal conductivities, the accuracy depends on the knowledge of
 333 thermophysical properties of the reference material with the TFM method.

334 3.6. Validation of the TFM heat of transition measurement

335 In this last section, Ti is the 'reference' material and NiTi is the 'studied'
 336 specimen. To observe the complete exothermic transformation from Austen-

337 ite to Martensite occurring in the NiTi specimen, temperature T_{ini} had to be
 338 above A_f and temperature T_0 below M_f . In this experiment, the following
 339 values were thus chosen: $T_{ini} = 100^\circ C$ and $T_0 = 0^\circ C$.

340 Experimental results obtained from homogeneous (using device presented
 341 in Fig. 3.a) and then from axially heterogeneous (using device presented in
 342 Fig. 3.b) cooling are presented and discussed.

343 3.6.1. Homogeneous cooling

344 Information and parameters chosen for this experiment are given in Table
 345 4. The experimental setup is described in Fig. 3.a.

Ref. Mat.	Studied Mat.	Exp. Setup	T_{ini}	T_0
Ti e = 0.51 mm	NiTi e = 0.39 mm	Fig. 1.a	$100^\circ C$	$0^\circ C$

Table 4: Information and parameters for TFM heat heat of transition measurement in the homogeneous case.

346 Figure 10.a shows the temporal evolution of temperature measured in the
 347 Ti and NiTi specimens during homogeneous cooling experiment (Figure 3.a).

348 The Ti temperature decreasing curve obtained for the Ti specimen is
 349 exponential like. However, for the NiTi specimen, two bumps due to the two
 350 exothermic phase transformations are noted, from Austenite to R-phase and
 351 from R-phase to Martensite, successively. The two specimens coolings started
 352 and finished to identical temperatures. Figure 10.b shows the cooling rate \dot{T}
 353 of Ti and NiTi specimens. The cooling rate range is between -1 and $-8K s^{-1}$.
 354 From these curves and from equations 18 and 19, heat source occurring in
 355 the NiTi specimen can be estimated.

356 Figure 11.a presents the ratio $\frac{\dot{q}}{|T|}$ results for the TFM method using a
 357 heat capacity for NiTi specimen equal to $500 \text{ Jkg}^{-1}\text{K}^{-1}$ [31, 32, 33]. DSC
 358 curve is also presented in black.

359 Global shapes of the curves obtained by the two techniques are similar;
 360 the amplitude of the peaks by the two methods are in good accordance. Ta-
 361 ble 5 summarizes the two peak temperatures, respectively noted T_{A-R} and
 362 T_{R-M} and the transformation temperature R_s , R_f , M_s and M_f for the two
 363 techniques (DSC (Figure 4) and TFM 0D): peak and transformation temper-
 364 atures are almost equal for the two techniques. From these values, starting
 365 temperature R_s and M_s for the two transformations appear to be very close
 366 for the two methods. Finishing temperature R_f and M_f are however lightly
 367 higher with the TFM method. Such a difference can partially be explained
 368 by thermal inertia effects in the DSC experiment: this inertia leads to un-
 369 derestimate finishing temperature of the transformation with this technique
 370 [33, 38]. With the TFM method, the specimen transforms naturally and
 371 independently of the environment; the TFM method exhibits no thermal in-
 372 ertia. Differences in the temperatures may also be due to the accuracy of the
 373 IR camera ($\pm 2^\circ\text{C}$) and of the DSC one.

374 Eventually, integrating the ratio $\frac{\dot{q}}{|T|}$ over temperature allows to estimate
 375 the energy released by the material versus temperature:

$$E = \int_{T_1}^T \frac{\dot{q}}{|T|} dT. \quad (20)$$

376 Its evolution is plotted versus temperature, for TFM and DSC techniques
 377 in Figure 11.b. For the two methods, transformed energy E is estimated
 378 between the initial starting temperature $T_1 = R_{si} = 74^\circ\text{C}$ and the cur-

$^{\circ}C$	DSC	TFM 0D	TFM 1D
T_{A-R}	58	60	59
T_{R-M}	28	32	30
R_s	62	63	62
R_f	53	57	54
M_s	39	39	39
M_f	12	17	19

Table 5: Peaks temperatures and transformation temperatures estimated from DSC, TFM 0D and TFM 1D.

379 rent temperature. The energy, for the transformation finishing temperature
380 $M_{fe} = 12^{\circ}C$ (see Figure 11.a), corresponding to the latent heat of transition
381 of the material, is estimated to be $19 Jg^{-1}$ for the TFM method. From the
382 DSC curve, the latent heat of transition is estimated to be $19.5 Jg^{-1}$, using
383 the baseline plotted in Figure 11.a. The results using the TFM method and
384 DSC are in good agreement.

385 For the TFM method, the main issue is the knowledge of the thermo-
386 physical properties of the material. A similar drawback occurs for the DSC,
387 where the choice of the baseline is the key point to realize quantitative la-
388 tent heat of transition measurements [23]. The two techniques are however
389 quantitatively in good agreements.

390 3.6.2. One dimensional heterogeneous cooling

391 Information and parameters chosen for this experiment are given in Table
392 6.

393 Spatio-temporal evolution along an axial profile is plotted for Ti specimen

Ref. Mat.	Studied Mat.	Exp. Setup	T_{ini}	T_0
Ti e = 0.51 mm	NiTi e = 0.39 mm	Fig. 1.b	100°C	0°C

Table 6: Information and parameters for TFM heat of transition measurement in the heterogeneous case.

394 in Figure 12.a and for NiTi specimen in Figure 12.b during heterogeneous
395 cooling (Figure 3.b). In Figures 12.c.d, temporal evolution of Ti and NiTi
396 specimens temperatures are respectively plotted for three pixels (pixel 65,
397 100 and 150) located at different distances of the thermal mass. At the be-
398 ginning of the experiment, all points had identical temperature and difference
399 of temperature appeared during cooling. At the end of the experiment, the
400 thermal mass was still hot and conductivity occurred in the specimens: pixels
401 close to the thermal mass were hotter than those close to the free edge (Fig-
402 ures 12.e.f). In the Ti specimen, natural cooling of every pixel was observed,
403 as during the 0D experiment. Additionally for NiTi specimen (Figure 12.d),
404 the two phase transformations from Austenite to R-phase and from R-phase
405 to Martensite can be observed. Figures 12.e.f eventually show the axial ther-
406 mal profiles of the two specimens at different times. However, for the NiTi
407 specimen, bumps appeared around times $t=10s$ and $t=20s$ in the thermal
408 profiles due to exothermic phase transformations occurring in the specimen.

409 The ratio $\frac{\dot{q}}{|T|}$ was estimated from 1D thermal profiles (Figure 13.a), using
410 a heat capacity for NiTi specimen equal to $500 Jkg^{-1}K^{-1}$ [31, 32, 33] and a
411 thermal conductivity of $11 Wm^{-1}K^{-1}$. Current study [33] shows that ther-
412 mal conductivity can be considered identical for Austenite and Martensite

413 phases. The spatio-temporal evolution of this ratio is plotted in Figure 13.b.
414 The spatio temporal propagation of the two phase transformations, from
415 Austenite to R-phase and from R-phase to Martensite are clearly visible: the
416 transformation started from the bottom (fast cooling) and finished to the top
417 (slow cooling due to thermal mass inertia) of the specimen.

418 The ratio $\frac{\dot{q}}{|T|}$ calculated with the TFM method is plotted in Figure 13.c,
419 versus specimen temperature, for pixels 65, 100 and 150 in red, blue and green
420 respectively. The ratio $\frac{\dot{q}}{|T|}$ obtained with DSC is also plotted. Qualitatively,
421 the ratios estimated for the three pixels are well superimposed. The peak
422 temperatures and the transformation temperatures for the two techniques
423 (DSC and TFM 1D) are given in Table 2. The peaks obtained with the TFM
424 method and with the DSC are in good agreement. As in the homogeneous
425 case, transformation temperatures estimated with the TFM and DSC (Figure
426 4) methods are in good agreement. As in the homogeneous case, thermal
427 inertia effects are once again observable in the DSC method.

428 Evolution of the energy released as function of the temperature during
429 the transformation is also plotted in Figure 13.d. It is estimated from TFM
430 technique for considered pixels and from DSC for the baseline presented in
431 Figure 13.c. Evolution of the energy is similar for the two techniques. The
432 latent heat of transition obtained from TFM method is $17.5 \pm 1 \text{ Jg}^{-1}$ for all
433 considered pixels and is slightly lower than the one estimated by DSC. This
434 error is partially due to the underestimation of the heat sources with the
435 process used, but also due to some experimental constraints: as explained,
436 the room temperature was $T_0 = 0^\circ\text{C}$ (to avoid freezing problems on the
437 window and on the specimen) which is close to M_f . In the heterogeneous case,

438 the final temperature of every pixel is not T_0 but lightly above, as observed
439 in Figures 12.c.d. Thus, in a part of the specimen, the phase transformation
440 did not occurred totally and released less energy.

441 However, knowledge of materials thermophysical properties can affect
442 results. Faulkner et al. [39] measured conductivity coefficients equal to
443 $14 \text{ Wm}^{-1}\text{K}^{-1}$ and $28 \text{ Wm}^{-1}\text{K}^{-1}$ for martensite and austenite, respectively.
444 In this study, thermal conductivity of k_{NiTi} was assumed constant ($11 \text{ Wm}^{-1}\text{K}^{-1}$)
445 and independent of the considered phase, as measured in [33]. Figure 14 yet
446 shows the evolution with the temperature of the terms involved in the equa-
447 tion 19 to estimate massic heat sources \dot{q} in NiTi sample for pixels 60 to 70.
448 Red curve shows the heat storage term, the blue one is for conduction in the
449 sample and the green one represents heat losses. Adding these terms leads
450 to the red curve plotted in Figure 13.c. Main terms are linked to the storage
451 one (red) and to heat losses (green). The conduction term (blue) is almost
452 negligible for temperature above 20° C . Thus, the accuracy of the k_{NiTi} is
453 not important in that study.

454 The TFM method in an heterogeneous case exhibits yet quantitative re-
455 sults in good agreement with those obtained by DSC. Note that in this study,
456 the chosen material had homogeneous transformation behavior. As the de-
457 termination of the properties is local, this technique would allow to determine
458 local latent heat of transition even if the material exhibited heterogeneous
459 transformation behavior.

460 4. Conclusion

461 Thermal Field Measurement (TFM) method has been developed and used
462 to estimate heat capacity, thermal conductivity and latent heat of transition
463 of materials. Advantages of this original method are (i) the non-contact as-
464 pect, measuring temperature with an infrared camera, while others methods
465 are with contacting methods and (ii) the local aspect of the measurement in
466 the heterogeneous case while other method are global. This last point is very
467 interesting in the case of heterogeneous material. (iii) The absence of inertia
468 effect as in DSC measurement.

469 The experimental setup to perform the measurement was based on the
470 simultaneous observation, with an infrared camera, of the natural cooling of
471 two specimens: a 'reference' and a 'studied' material. Titanium was used as
472 'reference' specimen to estimate convection and radiation heat losses.

473 Firstly, Vanadium has been used to validate the method abilities to es-
474 timate thermophysical properties. The TFM method has been proved to be
475 able to provide an accurate measurement of heat capacity C and local ther-
476 mal conductivity k of Vanadium. Results obtained from TFM techniques,
477 classical DSC, laser flash method and literature were in good agreement. Sec-
478 ondly, NiTi specimen was studied and chosen for its exothermic thermally
479 induced phase transformation. Latent heat of transition of this material was
480 estimated during homogeneous and heterogeneous thermal cases. Results
481 obtained with this technique and with DSC are in good agreement.

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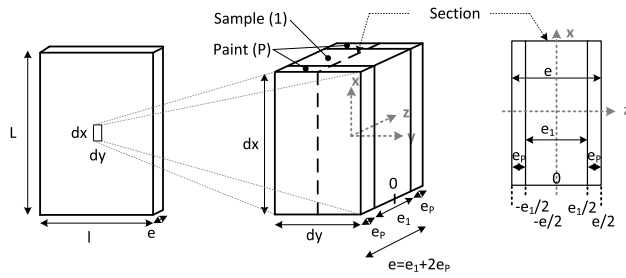


Figure 1: Specimen of thickness e_1 coated with the two paint layers of thickness e_P .

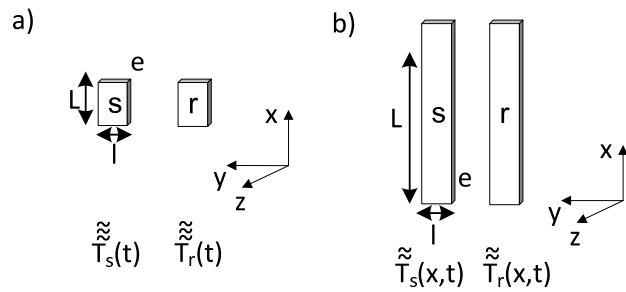


Figure 2: Reference (r) and Studied (s) specimens configurations in (a) homogeneous (0D) and (b) heterogeneous (1D) cooling.

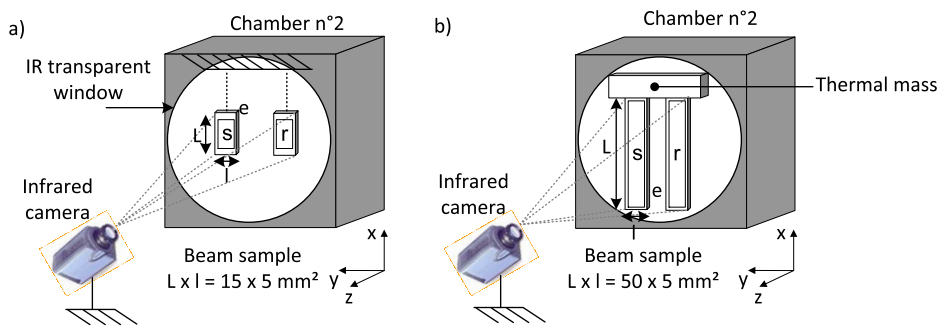


Figure 3: Experimental setup proposed to obtain an (a) homogeneous (0D) and (b) an heterogeneous (1D) cooling.

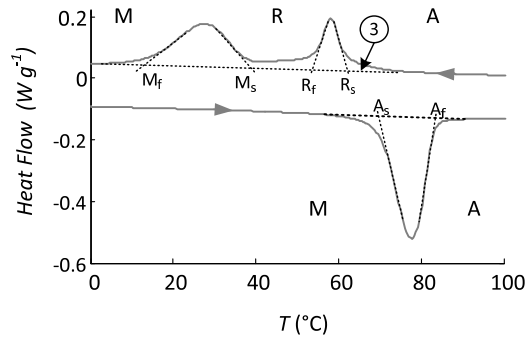


Figure 4: Differential Scanning Calorimetry thermogram of a NiTi DSC specimen.

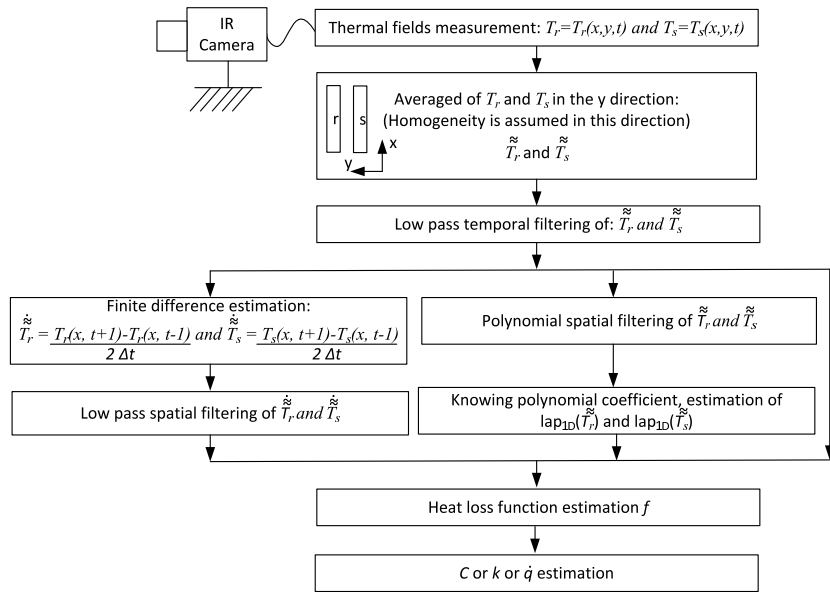


Figure 5: Data processing flow chart.

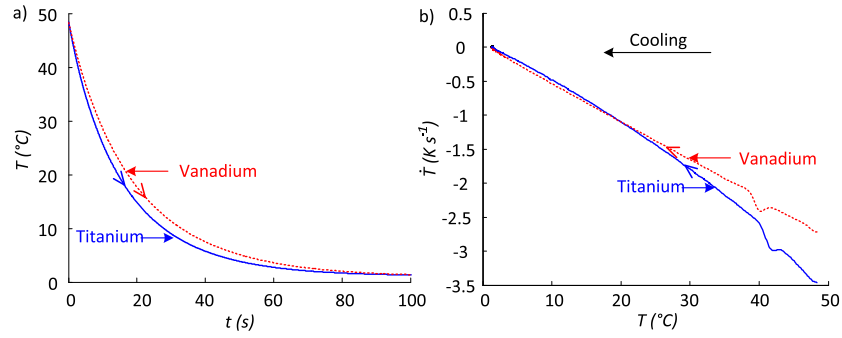


Figure 6: Homogeneous natural cooling of Titanium and Vanadium specimens. a) Temperature versus time and b) Temperature rates versus temperature.

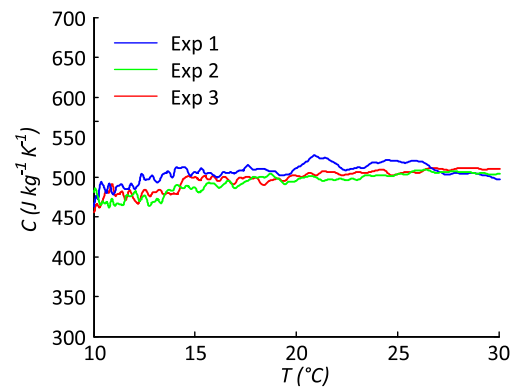


Figure 7: Heat capacity estimation of Vanadium for three distinct experiments.

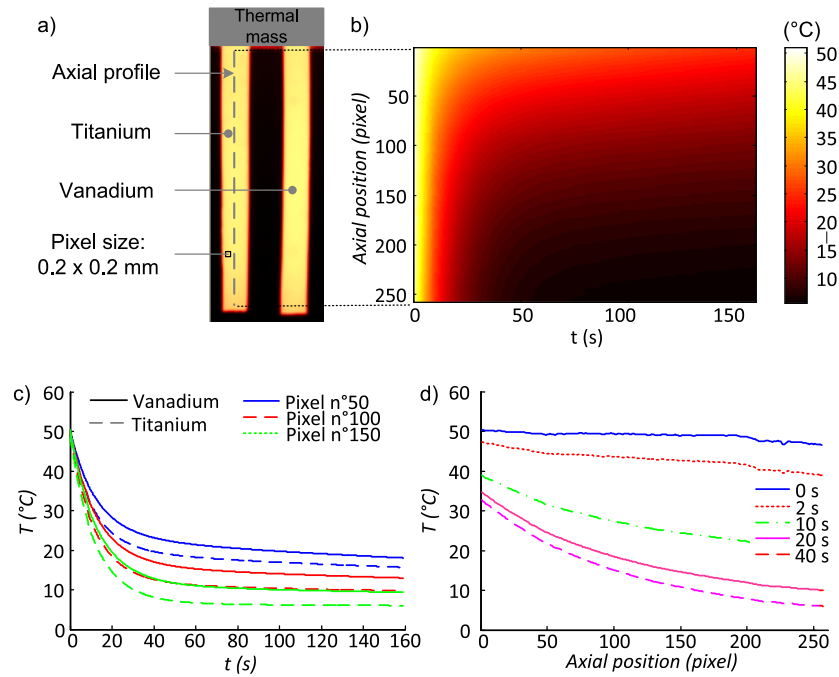


Figure 8: Thermal responses for Titanium and Vanadium specimens in 1D experiment. (a) Thermal image at a given time showing the two specimens. (b) Spatio-temporal representation of temperature along the axial profile plotted in (a) for Titanium specimen. (c) Temporal evolution of the temperature in three different localizations. (d) Axial thermal profiles at different times.

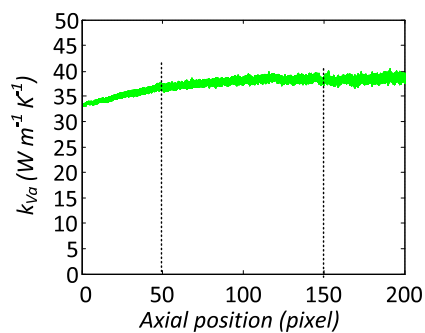


Figure 9: Local thermal conductivity estimation of Vanadium using $k_{Ti} = 20 \text{ W m}^{-1} \text{ K}^{-1}$.

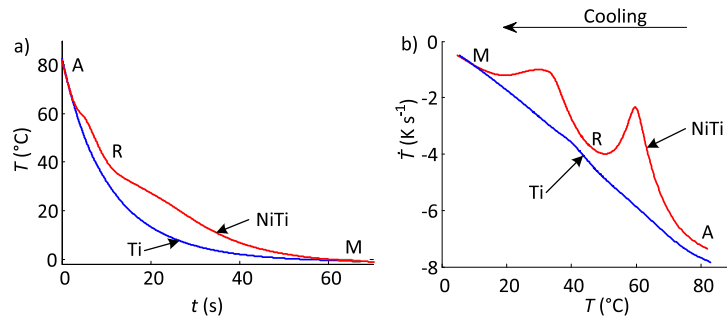


Figure 10: Homogeneous natural cooling of Titanium and NiTi specimens. a) Temperature versus time and b) Temperature rate versus temperature.

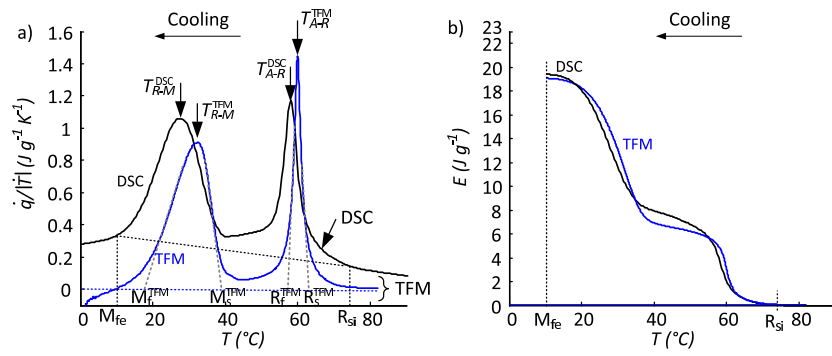


Figure 11: Estimation of transition heat - homogeneous natural cooling of the NiTi specimen. (a) Ratio $\frac{\dot{q}}{|\dot{T}|}$ and (b) energy evolution, measured by DSC and by TFM techniques.

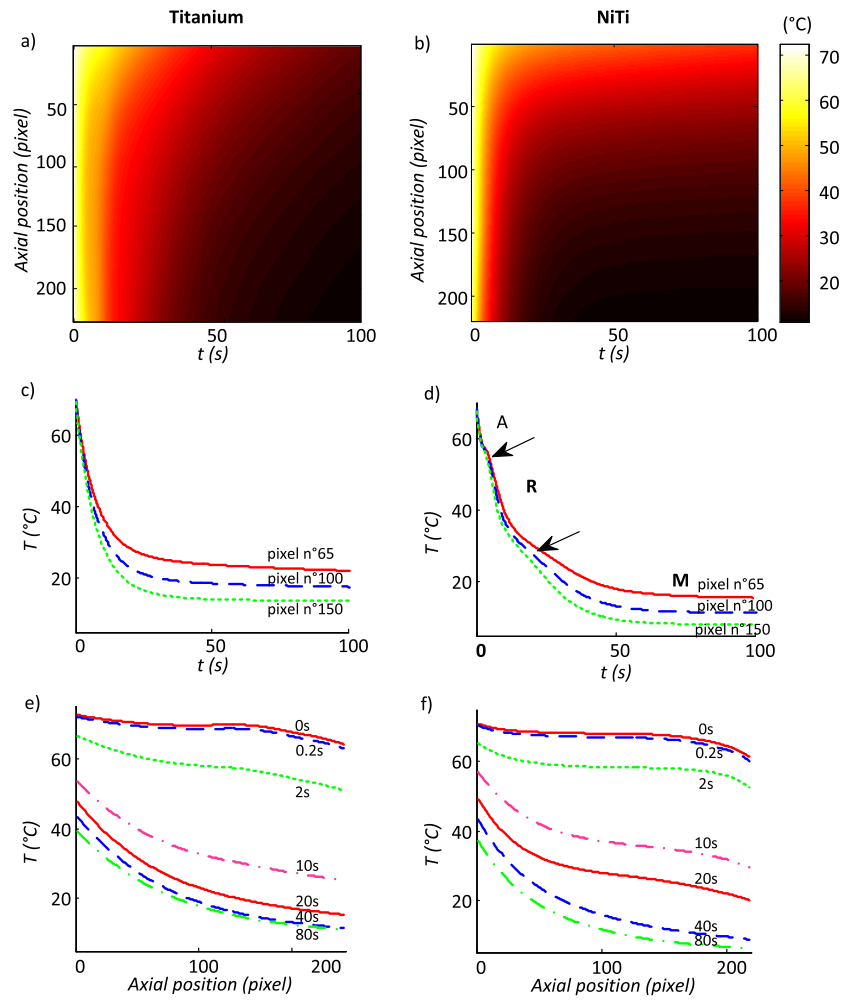


Figure 12: Thermal responses for Titanium and NiTi specimens in 1D experiment. Spatio-temporal representation of temperature along the axial profile for (a) Titanium and (b) NiTi specimen. Temporal evolution of the temperature in three different localizations for (c) Titanium and (d) NiTi specimen. Axial thermal profiles at different times for (e) Titanium and (f) NiTi specimen.

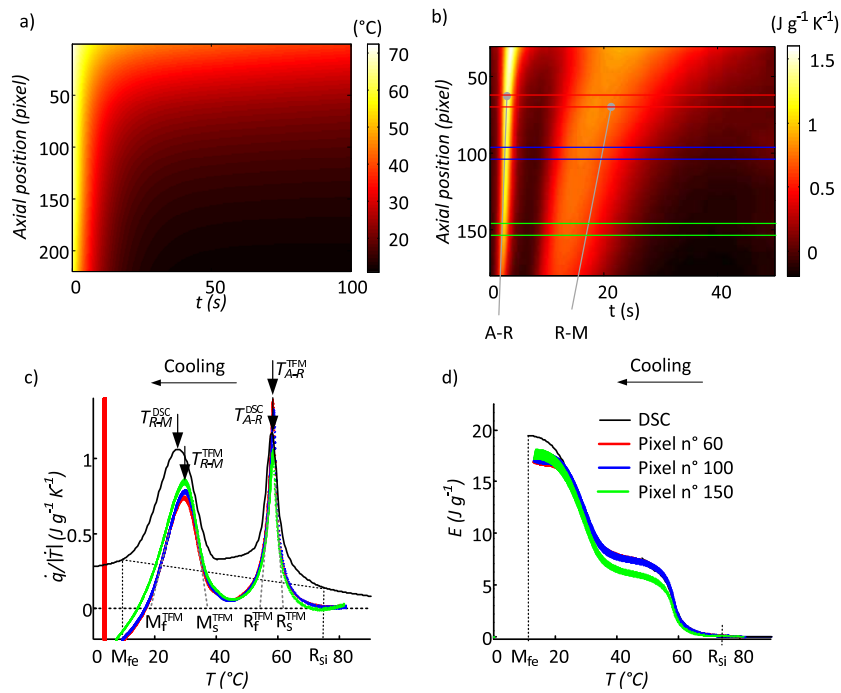


Figure 13: Estimation of transition heat - heterogeneous natural cooling of the NiTi specimen. (a) Spatio-temporal representation of temperature along the axial profile for NiTi specimen. (b) Spatio-temporal representation of ratio $\frac{\dot{q}}{|T\dot{}}|$ evaluated with TFM technique. (c) Comparison of the ratio calculated from DSC and TFM techniques and (d) Energy evolution during cooling for pixels 60 to 70, 95 to 105 and 145 to 155.

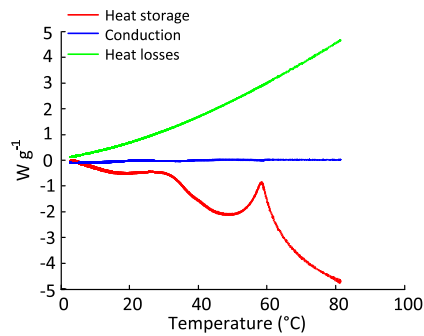


Figure 14: Evolution, with the temperature, of the terms involved in the massic heat sources estimation for NiTi sample (equation 19) for pixels 60 to 70.