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# NON-INVASIVE ANALYSIS OF ARTISTIC HERITAGE AND ARCHAEOLOGICAL FINDINGS BY TIME RESOLVED IR THERMOGRAPHY

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## Abstract

The structure and the preservation state of artistic heritage and archaeological findings have been studied by the analysis of the heat diffusion process in the sample. The investigations have been performed by non-invasive time resolved infrared thermography (IRT). Thickness maps, buried defects detection, inhomogeneity and corrosion analysis, as well as the quality check of welding and reinforcements elements, have been performed on the studied samples.

**Keywords:** cultural heritage, infrared thermography

## Introduction

Mainly due to its non-invasive (non-destructive, non-contact) nature, infrared thermography (IRT) has been recently widely used to investigate artistic heritage and archaeological findings. Thermography provides a temperature ($T$) monitoring of different sample surface areas and makes possible to perform a time resolved analysis of the heat diffusion process in the sample, providing information on its subsurface structure (for instance [1, 2] and references therein).

The results reported in the present paper have been obtained by a particular photothermal IR thermographic configuration (flash pulse method). In the used configuration, a thermal perturbation is generated at the sample surface by absorption of the light produced by two or more flash lamps. That gives rise to a fast (few milliseconds) temperature rise at the lighted surface, followed by a decay of the temperature value which depends on the heat diffusion process inside the sample. Deviations from the expected $T$ *vs.* time ($t$) behaviour reveals a local variation of the thermal properties which can be connected to the presence of inhomogeneities, corroded parts, defects (disbonding, delaminations, voids) or any thermal barrier. Results will be also presented showing how IRT enabled us to detect the position, and check the quality, of welding and reinforcement elements sited under the observed sample surface.

Finally it is worthwhile to note that, for homogeneous material, when the thermal diffusivity $D$ is known, thermography provides, by the analysis of the surface

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temperature decay, a simple method for the determination of the sample thickness even when one of the two surfaces is not mechanically or optically accessible. On the other way round, the thermal diffusivity of a given material can be determined by analysing homogeneous pieces of known geometry.

## Experimental

The thermographic method is based on the analysis of the infrared (IR) radiation emitted by a sample. The main element of a thermographic set-up is an IR TV camera, the detector of which is an array of elements sensitive to the IR radiation. The signal generated by each element depends on the intensity and wavelength of the radiation incident on it. Since, according to the Stefan–Boltzmann law, the radiation spectra emitted by each body strongly depends on its temperature, it is possible, by the IR camera, to obtain a temperature map of the sample surface. In particular, a series of temperature maps can be recorded after a short thermal perturbation of the sample surface (flash pulse method [3]). What we get in this way, is the temperature variation *vs.* time for different areas of the sample surface. As already mentioned, since the temperature decay at the surface depends on the heat diffusion process inside the sample, we can therefore obtain, by a non-destructive (ND) way, information on the sample subsurface structure. In Fig. 1 a scheme of the experimental set-up is reported. The IR camera detector was an array of 256×256 InSb elements operating in the 3÷5 μm wavelength range. The camera was equipped with properly coated germanium window and optics. The maximum acquisition rate was 60 frames/s. The thermal perturbation was obtained by absorption of light produced by a set of up to 3 kW powerful flash lamps. The light pulse duration was 2.5 ms at half height of its intensity peak. The IR signal generated by the camera is finally collected by an image converter and sent to a computer.

Some of the studied sample surfaces have been coated with easily removable colloidal graphite in order to increase emissivity, to minimise the IR reflections and

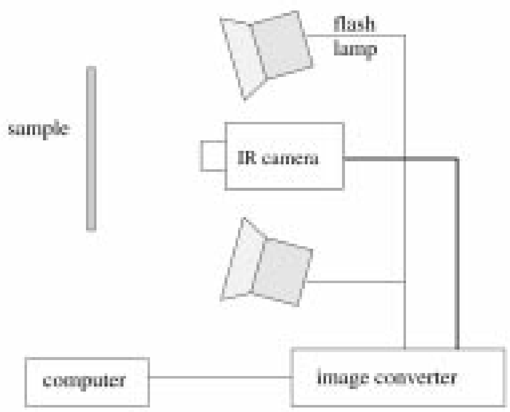


**Fig. 1** Experimental set-up

to improve the light absorption homogeneity. Moreover, IR filters were placed in front of the flash lamps to prevent the spurious reflections of the IR radiation they emit. Concerning data processing, a pixel by pixel subtraction of a cold frame (taken before the flash pulse) from the images of a sequence, was performed to remove emissivity inhomogeneity effects. Finally, a normalisation of the signal values to the first frame after the flash onset, was performed in order to compare the time evolution of the signals from different pixels of the same frame.

The description of the surface temperature change is derived from the collected IR signal, by a theory valid for unidimensional heat diffusion processes. Let us consider a homogeneous material slab having thickness $L$, density ρ, specific heat $c_p$ and thermal conductivity $k$, the surface of which is lighted at the instant $t$=0 by short pulse. If the sample is opaque to the incident radiation, a certain amount of heat is generated by light absorption at the sample surface. The subsequent heat diffusion into the sample gives rise to a local temperature change $\Delta T(x,t)$ which depends on depth $x$ and time $t$. If the light pulse duration can be neglected, compared with the time needed by the heat to diffuse through the slab section, and provided the heat losses toward the environment can be neglected as well, the temperature variation is described by the following equation [4, 5]:

$$\Delta T(x,t)=\frac{Q}{\sqrt{\rho c_p k}}\frac{\sqrt{D}}{L}\left[1+2\sum_{n=1}^{\infty}\cos\left(\frac{n\pi x}{L}\right)\exp\left(-\frac{n^2\pi^2}{L^2}Dt\right)\right] \tag{1}$$

which becomes, at the lighted surface ($x$=0):

$$\Delta T(0,t)=\frac{Q}{\sqrt{\rho c_p k}}\frac{\sqrt{D}}{L}\left[1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2}{L^2}Dt\right)\right] \tag{2}$$

where $Q$ is absorbed surface energy density.

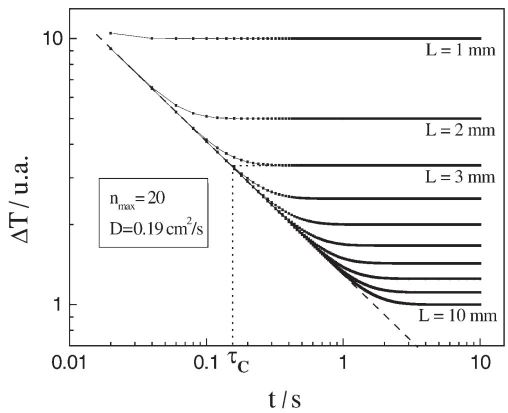


**Fig. 2** Surface temperature decay curves calculated for different thickness $L$ values in the case of material whose thermal diffusivity value is $D$=0.19 cm$^2$ s$^{-1}$

In Fig. 2 $\Delta T(0,t)$ is reported as a function of time on a log-log plot. The reported curves, obtained from Eq. (2) assuming $Q/\rho c_p=1$ and computing the series with a number $n_{max}=20$ of terms, refer to ten different thickness ($L$=0.1÷1 cm) of material, the thermal diffusivity of which is $D$=0.19 cm$^2$ s$^{-1}$ (the chosen $D$ value being the one of a particular kind of bronze investigated in the present work).

In the curves of the graph in Fig. 2, two different behaviours are clearly shown. Initially, while the heat diffuses through the sample, the temperature decay is $\propto t^{-1/2}$, as expected for the heat diffusion in a semi-infinite homogeneous material for which the temperature decay at the surface, after the flash pulse absorption, is known to be given by the expression [4]

$$\Delta T(0,t)_{L=\infty} = \frac{Q}{\sqrt{\rho c_p k}} \frac{1}{\sqrt{\pi t}} \tag{3}$$

(such behaviour is represented in the graph by the dashed line). After the heat reaches the back surface, the temperature rapidly stabilises to the thermal equilibrium value $T_{room}+\Delta T(0,\infty)$ where

$$\Delta T(0,\infty)=\frac{Q}{\sqrt{\rho c_p k}} \frac{\sqrt{D}}{L} \tag{4}$$

The crossing point between the two linear behaviours of Eqs (3) and (4) defines the crossing time $\tau_c$ having the following expression:

$$\tau_c=L^2/\pi D \tag{5}$$

so that from an experimental point of view, the sample thickness $L$ can be immediately obtained from the crossing time $\tau_c$ determination once the $D$ value is known. On the other hand, when the sample geometry is known, local defects and inhomogeneities locally change the thermal parameters value giving rise to anomalous temperature variation with respect to the one expected for a homogeneous material.

## Results and discussion

The results reported in this paper concern four different samples studied by thermography: the bronze copy of the equestrian statue of the Roman emperor Marco Aurelio sited in Piazza del Campidoglio in Rome, two pieces of Phoenicians jewellery, one Roman coin made in the 1$^{st}$ century A. D.

*The statue of Marco Aurelio*

Due to its large mass, one of the main needs in the statue copy making, was to check the thickness homogeneity of the bronze and the presence of defects (voids, cracks) in particular where the mechanical stress was particularly large after the assemblage of the statue components.

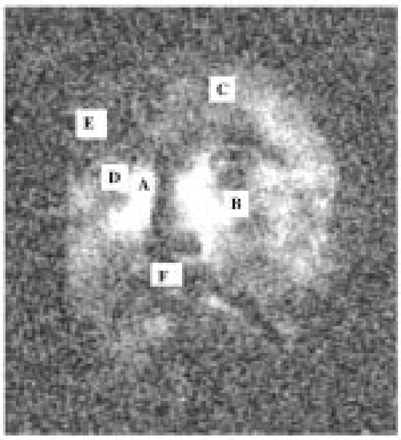


**Fig. 3** Thermograph of the face of the Marco Aurelio statue. Capital letters indicate the areas whose corresponding thickness is reported in Table 1

To perform a thickness study of some parts of the statue copy, we have first recorded the $\Delta T(x,t)$ *vs.* $t$ behaviour on different pieces of known thickness, made using the same bronze of the copy. We obtained in this way an experimental set of $\tau_c(L)$ values. Plotting $\tau_c$ as a function of $L^2$ we got, as expected from Eq. (5), a straight line from the slope of which the material thermal diffusivity value $D$=0.19 cm$^2$ s$^{-1}$ could be determined. Finally, we performed a thickness study of the rider's face based on $\tau_c$ determination. The results, based on the analysis of a series of thermographs (one of them being represented in Fig. 3), are reported in Table 1. It is worthwhile to remark how the above result has been obtained while the inner surface was neither mechanically nor optically accessible.

**Table 1** Bronze thickness values detected at the rider's face. Capital letters refers to the selected areas indicated on the thermograph of Fig. 3

| | Ref. in Fig. 3 | Thickness/mm±0.5 |
|---|---|---|
| Between nose and eyes | A | 4.8 |
| Below the eyes | B | 6.0 |
| Temple | C | 6.2 |
| Eyes | D | 6.3 |
| Lateral forehead | E | 7.1 |
| Below the nostril | F | 9.2 |

One more goal of the thermographic analysis carried out on the statue was to detect the position, and check the quality, of inner welding and reinforcements. In the thermograph of Fig. 4 the detection of a homogeneous internal welding line with a superimposed reinforcement plate is clearly evident. In Fig. 5 finally, the thermograph shows two internal voids (pointed by arrows) detected in one of the bronze part be-

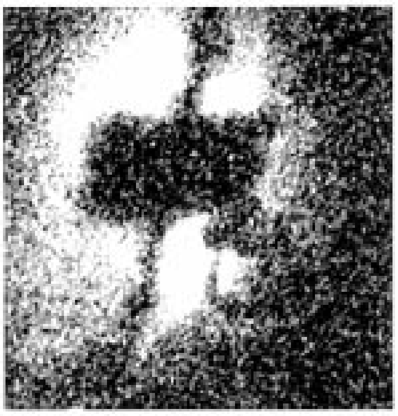

**Fig. 4** Thermograph of one side of the horse. An inner welding line with a reinforcement plate is clearly evident

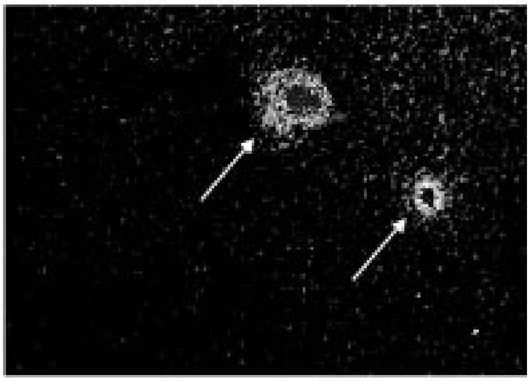

**Fig. 5** Thermograph putting on evidence the presence of two inner voids (pointed by arrows) in one of the bronze part made for the statue

fore its welding to the statue. Further details about the copy of the statue of Marco Aurelio can be found in [6].

*Phoenicians jewellery*

Thermographic analysis has been also performed on two pieces of Phoenicians jewellery ([7] and references therein for related archaeological and metallurgical aspects), in order to collect the needed structural information before a restoration work. In one case, the studied sample was an earring and the purpose was to detect bad mechanical contacts between a gold wire coil and its support and look for the possible presence of hidden welding and empty parts. The investigation result is shown in the thermograph of Fig. 6 where the coil light parts, appearing like horizontal white stripes inside the circled area, represent the hottest ones. They are localised where an air gap,

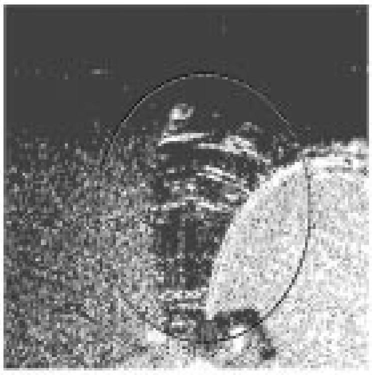

**Fig. 6** Thermograph of a Phoenicians earring. Bad mechanical contacts between a gold wire coil and its support correspond to the white parts

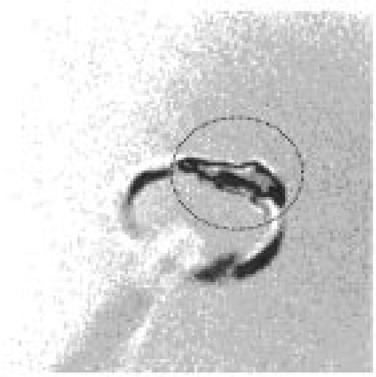

**Fig. 7** Thermograph of a Phoenicians ring. In the circled area, the volume of material used to weld the collet to the ring support can be easily observed, even though partly hidden under the outer gold leaf coating

which acts as a thermal barrier, is present between wire and support. A second analysed jewel consists in a ring. By the thermograph reported in Fig. 7 was possible in this case, to determine the volume of material, partly hidden under the outer gold leaf coating, used to weld the collet to the ring support.

*Roman coin*

Finally, a Roman coin (photograph on the right side of Fig. 8), made in the 1st century A. D., has been analysed. In the thermograph of Fig. 8 (left side) two different areas are evident showing a clear inhomogeneity of the material composition. It should be noted that such inhomogeneity was not evidenced by the optical analysis of the well-finished surface. Thermographic analysis was also performed coating the coin surface with graphite in order to prevent absorption and emissivity inhomogeneity. Finally, it is worth men-

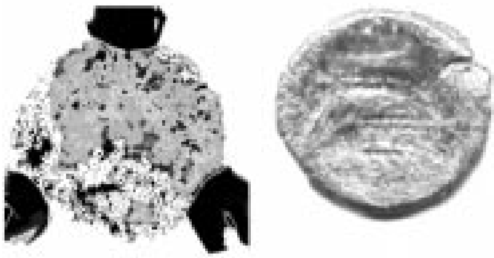

**Fig. 8** Thermograph of a Roman coin (left side). Two main different areas reveal an inhomogeneity in the material composition. On the right side the corresponding photograph from which no evidence of such inhomogeneity can be detected

tioning that the results obtained by thermography well agree with those ones from the X-ray analysis performed on the same sample (not reported here).

## Conclusions

A non-invasive photothermal investigation of the structure and the preservation state of artistic heritage and archaeological findings have been presented. The used technique was IR thermography in the front flash configuration. By this technique the heat diffusion process inside the sample can be analysed enabling us to get information on parts of the sample in a non-destructive way, being this last requirement a fundamental one for studying artistic and archaeological objects. The reported results concern quantitative characterisation (thickness determination) and subsurface structure monitoring (detection of inhomogeneities and thermal barrier elements).

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