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ASSESSMENTS ON MATERIAL THICKNESS AND COATING IN LASER SPOT ACTIVE THERMOGRAPHY

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ABSTRACT

This work reports the results of an experimental investigation of the coupled effects of component thickness and paint coating on metal components surfaces, in surface temperature measurements by means of pulsed active thermograpy technique. A set of tests were performed using a steel US calibration block, with and without paint coating, where thermal energy is input on the target surface by means of a laser beam. The heating and cooling profiles are processed and and compared. It results that paint coating affects the transient thermal profiles and adequate average and calibration procedures allow correlating the profiles with the thickness.

Keywords: thermography, active thermography, emissivity.

INTRODUCTION

Thermography is a technique based on the acquisition of images in the infrared spectral band in order to measure the thermal response and behaviour of a component, a specimen, under give load conditions, let them be thermal or mechanical. These pieces of information can be obtained by adequate processing of surface temperature data. Thermal radiation phenomena occurs within a part of the electromagnetic spectrum which reange between about 0.1 to 100 µm. Each body, being at a temperature higher than 0K (-273.15°C), emits electromagnetic radiation, the amount of radiation emitted is related to the temperature and the surface state of the body, the higher the body temperature the higher the frequency of the waves emitted. The black body, by definition, owns the maximum emissive power. Emissivity is a critical parameter for thermographic measurements and its characterization is complex. Usually, the emissive properties of the observed surface can vary with temperature and in the different areas subjected to analysis. Therefore, it is immediate to understand how emissivity represents one of the main variables of temperature measurements by means of the thermographic technique. In application cases of mechanical, aerospace and naval materials and components, the variability of component surface conditions introduces degrees of complexity to the physical phenomenon. Variations in the surface properties of the component such as roughness, presence of scratches or highly irregular surfaces (weld beads), different colors of the surface or presence of corroded areas, presence of coating and / or lining, introduce many variables during the measurement process which, if not correctly evaluated, can introduce measurement errors. Two main technique are reported in literature concerning thermographic analysis. Passive Thermography (PT) is a non-destructive technique (NDT) for the analysis of the mechanical behavior of materials [3] [2] for determining, for example, the fatigue limit of steels [6]. In mechanical applications, PT is based on the acquisition and processing of surface temperature variation generated by mechanical loading, viscous phenomena and other dissipative and thermoelastic phenomena. Today several steps forward have been made and new thermographic techniques were developed, as Active Thermography (AT). AT refers to the use of the thermographic technique as a diagnostic tool for the non destructive detection of damage process and of the analysis of miscrostructural and physiscal properties of mechanical components by means of the analysis of the component thermal response. In particular a thermal impulse, single or repeated is input on the component surface and the thermal response in investigated bu means of the analysis of the thermal transients, in time and space, of surface temperature. The techniques developed for generating the thermal load on the component surface are various and lend themselves, each in a different way, to various applications. Furthermore, AT allows evaluating the thermal response in the surface plane highlighting differences in thermal behavior due to the anistropy of the material [1] [5]. One of the first techniques that has been developed is lamp active thermography which involves the introduction of thermal loading through halogen lamps. This technique is suggested for the diagnosis of very large defects, even in anisotropic materials, such as fiber composites for the detection of delaminations [4]. Many applications of this kind have been used in the aerospace and naval sectors. Another widely used technique is laser spot active thermography. When a very concentrated thermal loading is required, the use of a laser source is indicated. Usually impulsive thermal loads are applied, to characterize behaviours highlighted by short transients, like very small defects. There are other techniques such as heat gun active thermography or vibrothermography. One of the main problems of the aforementioned techniques is that the surface state (roughness, curvature, color...) of the sample under examination introduces a non trivial degree of complexity of the measurement due to the problems related to the thermal emissivity, transmissivity and reflectivity characteristics. Emissivity still represents one of the main variables to be assessed in the thermography measurements. To maximize emissivity and limit the errors due to reflected radiation and surface roughness black paint is applied by spray deposition. This way the layer thickness cannot be controlled. The paint layer operates also as a filter. In PT, the surface temperature map is due to phenomena generated below the paint layer, in the volume of the specimen and the volume temperature variation is slow. Faster and cyclic transients, like thermoelastic effects, can be detected by means of adequate acquisition frequency. In AT the surface temperature is related to diffusion phenomena of thermal energy input through the surface from an external source. In this case, if a paint layer is applied to the surface, the thermal energy crosses two interfaces and diffuses in two means, the paint layer and the component. The thickness of the two means will accordingly affect the thermal transient. Then the detected thermal transient is affected by the coupled phenomena. The presence of the paint layer can then affect the reliability of temperature measurements in particular during temperature transients (heating, cooling, diffusion, conduction phenomena). The aim of this work is to evaluate the influence of the paint coating on AT thermal measurement run on a steel blocks excited with laser pulses. The coupled influence of block thickness will also be investigated.

MATERIALS AND METHOD

The analysis was performed on a steel calibration block for ultrasonic testing. The test article was chosen for to study the coupled influence of test article thickness and coating layer on temperature measurements by means of AT. The geometry is shaped in 10 steps with a constant width of 25mm x 50mm and an increasing thickness of 2.5 and 10 mm steps. In Figure 1 the picture of the block is reported. The bottom flat surface of the block was coated by means of a commercial black opaque spray paint, as indicated in literature. The average thickness of the paint coat was measured by means of coating thickness tester CG204 by EXTECH Instrumens (res. 0.1 μm). Paint layer thickness was measured in 50 points equispaced along the four edges of the block. In Figure 2 the 50 equispaced measured points distribution is reported. In each point, 3 measurements were performed. Average thickness measurements for each point are reported in Table 1, showing a non uniform distribution of paint coating on the investigated surface. Average coating thickness is 7.16 μm and 1.57 μm (22%) standard deviation.

Fig. 1 – Test piece.

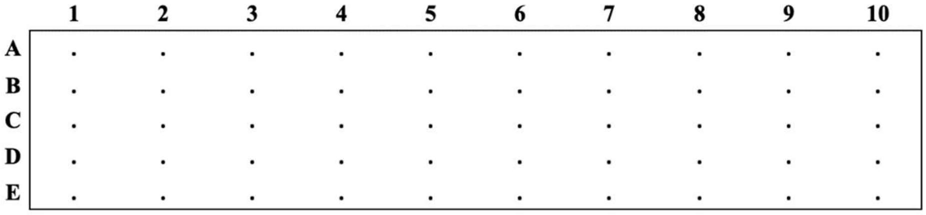

Fig. 2 – Paint coating measured points.

The AT technique provides the measurement of the sample surface temperature undergoing an external thermal excitation, applied by means of a thermal pulse (Pulsed Technique) obtained by means of a laser or other sources. The wavelength and the extension of the thermal source, the energy distribution on the target spot, the time curve of energy emission of the source are factors which can affect the thermal response of the investigated surface. In more detail, in present case the external thermal excitation consists of a laser beam, (maximum power 50 W, spot diameter 6 mm). The laser spot has a gaussian power distribution. An IR thermal camera FLIR A6751sc (Wilsonville, OR, USA) (sensitivity lower than 20 mK and 3–5 μm spectral range) (see Figure 3).

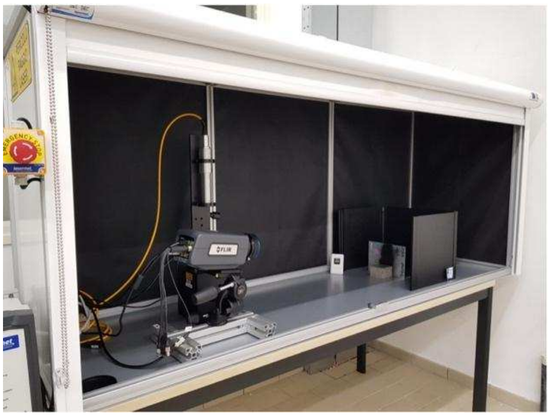

Fig. 3 – Active thermography test bench.

The specimen bottom surface was tested with laser spot pulsed thermography technique. Hence each test was performed on the flat surface pointing the laser spot in the center of each step with different thickness, with and without paint coating. In Figure 4 the step identification numbers corresponding to laser target and in Figure 5 the measurement ROI are reported respectively. The laser power was set to 12.5 W and the power-on time was set to 3 s for a total estimated energy input of 37,5 J. Surface temperature maps were acquired. Thermal camera was positioned 510 mm distant from the target surface. Emissivity values were experimentally set for paint coated and non coated surfaces. A thermal map acquisition was performed for a time period including 5 second before laser impulse emission and 5 second after. Acquisition frequency is 100 Hz. The thermal data were processed as follows. The area of the target spot was identified and a 10mmx25mm ROI corresponding to the projection of the step (Figure 5) was isolated to extract the heating and cooling time profile, for each acquisition, for each specimen thickness, with and without paint coating. In particular two sets of time data were obtained from the ROI: the maximum temperature $T_{max}(t)$ and the average temperature $T_{aveROI}(t)$, averaged on the ROI. Then two parameters quantifying the surface thermal increment with respect the room temperature T_{amb} were processed $\Delta T_{max}(t)$ and $\Delta T_{aveROI}(t)$ defined as follows:

$$\Delta T_{max}(t) = T_{max}(t) - T_{amb} \tag{1}$$

$$\Delta T_{aveROI}(t) = T_{aveROI}(t) - T_{amb} \tag{2}$$

The same acquisition and processing were performed but average calculation was run on an area corresponding to the projected step area, thus obtaining the parameters $T_{aveSTEP}(t)$ and $\Delta T_{aveSTEP}(t)$:

$$\Delta T_{aveSTEP}(t) = T_{aveSTEP}(t) - T_{amb} \tag{3}$$

By means of these four parameters, the block thermal response was characterized and the quality of the measurement, with and without paint, compared. The dimension of the ROI was selected basing on the distribution of the thickness of the layer of coating, to have in the ROI the average paint coating thickness obtained for the whole surface.

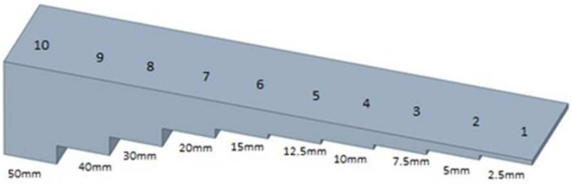

Fig. 4 – Step identification numbers.

Fig. 5 – ROI.

Table 1 – Average punctual thickness measures of paint coating.

μm	A	B	C	D	E
1	7,9	9,3	5,9	8,6	6
2	6,8	7,2	7,6	6,6	7,8
3	7,9	7,7	7,4	7,5	4,7
4	9,5	4,7	7,2	9,2	9,4
5	9,3	7,8	6,1	7,6	7,5
6	6,6	6,1	7,3	7,4	7,3
7	7,5	7,3	7,2	7,7	4,7
8	7,5	7,2	7,2	4,7	10,2
9	7,3	4,7	9,5	2,3	7,6
10	4,4	7,6	9,3	5,1	6,9

One measurement per point was acquired as repeteability was fund to be elevated. The tests were performed from Step 1 (thickness 2.5 mm) to Step 7 (thickness 20 mm). Since active thermography aims at measuring the thermal responses of tested areas of components, maximum temperature measurements are expected to be related to block thickness. For a given set of excitation parameters (in particular with the same power input of 12.5W), we expect to obtain different thermal responses for different block thickness due to different thermal capacity (according to same area and different thickness). In the first part of heating transient, when the thermal impulse is input through the paint coating surface, a temperature transient is expected, when the average temperature rapidly increases its value. After the transient a linear thermal increment follows, which is due to steel heat accumulation. Heat accumulation in a material volume follows the relations:

$$\delta q = C * \delta T \tag{4}$$

$$\delta q = P * \delta t \tag{5}$$

where q is the input energy [J], C the heat capacity [J/K], T the temperature [K], P the power of the energy input [W], t the time [s].

From Eq.5 we can easily approximate the heat accumulation process of the component with the following Eq.6

$$\frac{\delta q}{\delta t} = P = C * \frac{\delta T}{\delta t} \tag{6}$$

Since P can be assumed as constant during laser pulse, the heating process results to have a linear behaviour. Heat capacity is an extensive property, directly related to the specific heat capacity c [J/(kg*K)] the mass and then the volume of the material $V = A * s$ where s is the step thickness.

$$C = c * A * s \tag{7}$$

Given the same area A of the test article step, assuming that, for small paint layer and for short transients, heats propagates parallel and perpendicular to target surface, the heat capacity can be assumed inversely dependent on the thickness:

$$\frac{\delta T}{\delta t} = \frac{P}{A * c * s} \tag{8}$$

thus explaining the different trend of the heating and cooling profiles with increasing thickness.

RESULTS AND CONCLUSIONS

In Figure 6 the heating and cooling temperature profiles, normalized with respect to the maximum temperatures of each profile, are reported for two steps (Step 1 and Step 7 corresponding to 2.5 and 20 mm thickness respectively), with and without paint coating. As expected, for both steps it can be observed that the heating transient is slower for non coated than for coated surface, that is the diffusion in non coated surfaces is more effective than on coated one. This can be explained with the presence of the coating which acts as an interface to heat penetration through the steel surface, accumulating in the paint layer the heat which is then introduced in the steel. Thicker step show slower heating profiles as the thermal capacity of the corresponding larger volumes is higher. In cooling profiles these behaviours are confirmed.

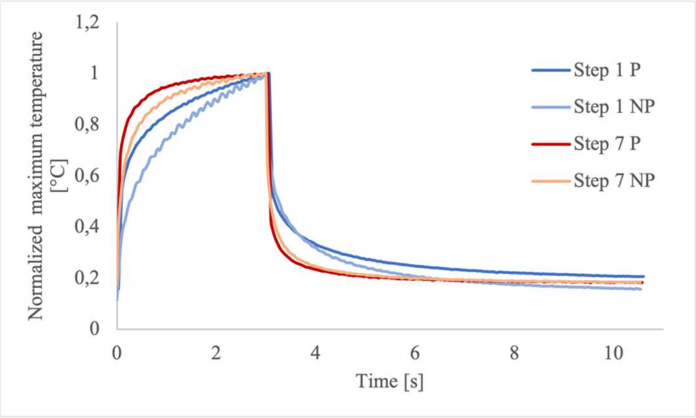

Fig. 6 – Normalized maximum temperature for non paint coated (NP) and paint coated (P) surfaces corresponding to Step 1 and Step 7.

The analysis of the results is then focused in investigating the coupled effect of paint coating and thickness. In the following figures the heating and cooling profiles for paint coated test article surface are reported. In particular in Figures 7 and 8 the heating and cooling profiles respectively for the spot ROI are reported for each step for test article with paint coating for the $\Delta T_{maxROI}(t)$ parameter. In Figures 9 and 10 respectively the corresponding profiles obtained for $\Delta T_{aveSTEP}(t)$ parameter that is the average temperature in time, over a surface corresponding to the projection of the step. In Figure 11 the maximum average temperature increment for test article with paint coating is reported in time log scale as an example.

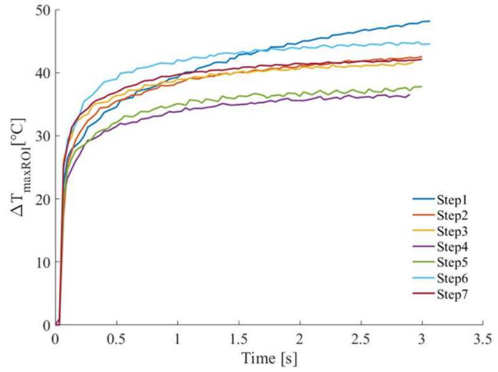

Fig. 7 – Maximum temperature increment/heating.

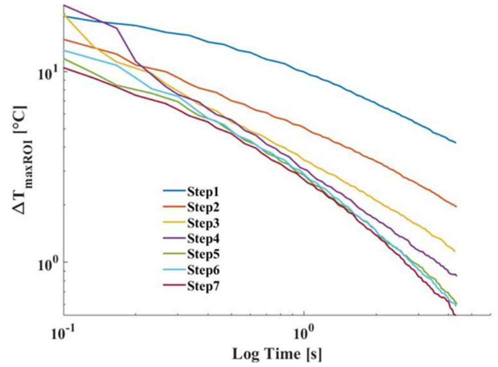

Fig. 8 – Maximum temperature increment/cooling.

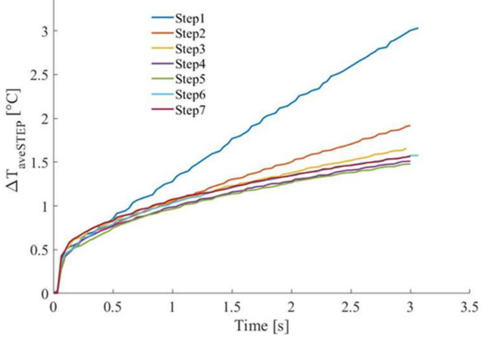

Fig. 9 – Maximum temperature increment/heating, average on step surface.

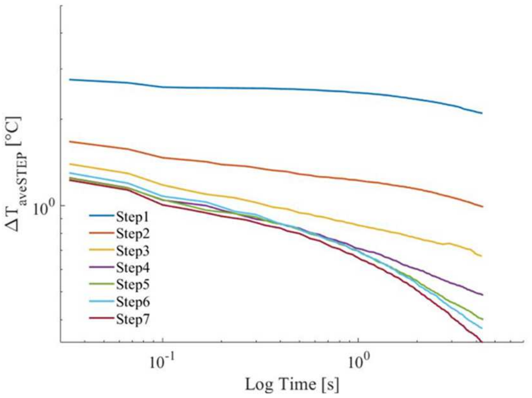

Fig. 10 – Maximum average increment/cooling, average on step surface.

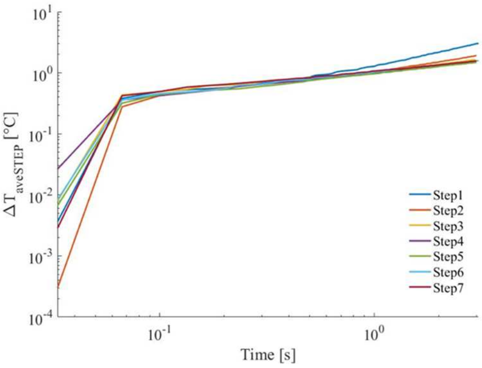

Fig. 11 – Maximum temperature increment/cooling, average on step surface - log scale.

In Figure 7 apparently no relation is evident between the trend of the heating profiles ant the tested thickness, while in 8 an apparent trend is observed, and in particular for thickness steps between 2.5 and 10 mm the cooling rates are increasing and are separated; for thickness steps equal and higher than 12.5 mm the cooling profiles tend to overlap. Two possible phenomena can explain these behaviours. For what concerns the heating transient, this behaviour can be related to the effects of the paint during short transient. In particular, when the laser input hits the surface, the energy propagates both parallel to the surface, that is in the coating, and perpendicularly that is towards the interface between the coating and the metal. A non perfectly uniform paint layer can generate non uniform diffusion effects and then non uniform surface temperature distribution. For what concerns the cooling profile, after a few seconds of cooling, the diffusion effects are dominant and the larger thermal capacity of larger volumes hides the transitory effects related to non uniform paint distribution, and then is possible to find a pattern between the cooling curves of the different tests. It also results that during a brief transient, the heating curves do not provide reliable information on sample thickness. Since there is a local effect on short transient which invalidates the tests, trying to assess the thermal phenomena on a larger scale, that is the temperature increment averaged on the step projected area in heating and cooling transients $\Delta T_{aveSTEP}(t)$, were plotted in Figures 9 and 10. In these plots two different trends on the heating curve can be pointed out. Both in heating and cooling profiles the curves related to different thickness show different slopes, the thinner steps heat and cool more rapidly than thickest ones. This trend can be observed up to 10 mm thickness then the curves overlap. In Figure 11 the logarithmic time scale points out clearly the presence of two contributions to surface temperature in short transients: one due to paint coating, in the first part of the time plot, and the following due to diffusion effects in the steel volume in the second part of the time plot. A further element can be added to the discussion. Paint coating is used to maximise the emissivity of the measured surface and to improve the reliability of the temperature acquired value. If the information on the thickness is required, than active termography can be used as a non contact technique. In general, the thickness estimation can be obtained by comparing the different transient radiance profiles, neglecting correctness of the temperature. If paint coating is present on the surface the emissivity is improved but an artifact is introduced altering the correct surface temperature measurement. Then averaging the temperature acquisition over a large surface allows to discriminate the different thicknesses.

CONCLUSIONS

Surface temperature monitoring can provide information on physical and structural properties, damage, geometry of components. Thermal contours can be acquired by means of infrared thermal cameras and the subsequent acquisition processing can provide the requested information. The reliability of temperature acquisition is related to several parameters as surface emissivity, roughness, acquisition frequency, environmental conditions...Black paint coating is used used in thermographic analysis to maximise emissivity and improve thermal measurements. In the present paper, the results of an experimental investigation, on the effect of the black paint coating on the acquisition of temperature in laser pulsed active thermography, are presented. The analysis is extended to the coupling effect of the thickness of the measured target. The main results can be summarized as follows. Laser spot active thermography technique allows to discriminate different thickness of specimens, for the same measured surface extension. This measurement is more reliable and the results are more evident if the thermal profiles are averaged over a surface rather than in a point or on a small ROI. The presence of a paint coating on the measured surface affects the heating and cooling transient temperature profiles and in particular a steeper slope is observed in painted surface indicating and heat storage in the coating which is released to the underlying surface in the subsequent instants. The opposite trend occurs in cooling transient where the paint coating release the stored heat immediately and filters the release of the heat energy stored in the metal volume. When a paint coating is present, a threshold value of thickness can be identified above which the ability of the thermographic method to discriminate the thickness is not effective. In thermographic acquisition, a paint coating can improve emissivity. This property reveals to be effective in passive thermographic acquisitions while in active thermography it introduces some complexities which can be taken into account by means an adequate data processing and calibration.

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