Thermal Variations in Static Tests on Plastics: a First Approach to the Fatigue Parameters Analysis

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ABSTRACT. *Following previous results showing that under the static loads it is also possible to detect the first plasticization of the specimens at the end of the thermoelastic phase, the authors conducted experimental trials to verify that this effect can be put in evidence in notched and unnotched PVC specimens. The goal was to define the real elastic phase also for material in which the elastic limit and the yield are not easily defined, differently from than that for steel. The results showed a variable thermal behaviour in the value of the thermoelastic limit and in the interval between this one and the yield in function of the distance from the notch. The limits so enhanced allow for following the paths of plasticization.*

INTRODUCTION

Several papers have correlated the fatigue limit of materials with the increment of the surface radiometric temperature in specimens under cyclic tensile loads, using thermal infrared imagery [1-8]. A new methodology to determine the fatigue limit using thermal increments was developed [1-4], allowing this limit and the whole fatigue curve to be evaluated in an extremely short time (Risitano method). The technique is reliable even when using a very limited number of specimens (theoretically only one). Many studies were carried out to define the energy in the fatigue and plasticity process [9-18]. The thermal variations have been correlated to the damping energy, which is stable and very limited when the applied stress is below the fatigue limit, but increases at every cycle when the stress exceeds it. The methodology leads to a new definition of the fatigue limit meaning: it is the maximum stress corresponding to the absolute elastic behaviour of the whole specimen and, consequently, to the beginning of the local plasticity.

Subsequent studies using real thermal scanners and image analysis showed that the thermo-elastic effect was also detected in the static field. The thermal variations were found to be proportional to the applied stress in the first elastic phase [19-22].

Based on the results obtained in the dynamic field, the authors carried out static tensile tests on different materials and mechanical elements and compared the results with those obtained by fatigue testing.

As indicated by thermo-elastic theory, and confirmed by tests previously performed on steel specimens, for tensile stress the thermal variations are negative and decrease linearly with the applied load. The gradient of the curve inverts the sign and the thermal variations become positive in the plastic phase. It is also possible to distinguish the variation in the slope of the thermal response in the elastic field. The applied load produces local plastic deformations which are great enough to affect the thermal behaviour. It was demonstrated that the change in slope is correlated to the end of a first totally elastic phase, and corresponds to the beginning of a different phase (micro-plastic strain) which cannot be detected in traditional curves [23]. When the stress is close to the fatigue limit a significant increase in temperature is produced, so reducing the effect of the decreasing temperature caused by the tensile stress [24].

DESCRIPTION OF THE INVESTIGATION

Following the results reported in [24] about tests performed on steel specimens, the authors use PVC specimens to verify its thermal behaviour under static loading. At the same time, the authors propose a reliable methodology to define real elastic and yield parameters in material for which they are not uniquely defined.

Therefore, this paper presents a study performed on various PVC specimens under static tensile loading using thermal infrared techniques to determine whether thermal behaviour can provide information regarding the elastic properties of the material. In particular, the area between the fatigue limit, coincident with the end of the totally elastic phase, and the static elastic limit, was investigated.

The purpose of the study is to consider that the real range of the totally elastic limit is not defined by the yield point, but by the previous stress limiting the thermo elastic behaviour of the material. In fact, in correspondence with such, the micro damage begins and, consequently, the micro cracks nucleation begins and the plastic process is already in progress. As previously described [24], the fatigue limit was defined as the beginning of the micro damage. Therefore, the point corresponding to the linear thermoplastic effect has to be linked with the fatigue limit.

In order to evaluate the correlation between the value of the thermoplastic stress limit (in correspondence with the slope variation from the initial linear phase in the stress-thermal variation curve) and the possibility of forecasting the plasticization paths as a function of the applied load, a series of notched (with through hole) and unnotched specimens was investigated. The specimens are flat 30.2 x 4.7 x 200 mm (width x thickness x length) rectangular bars in plastic material (PVC) with different central holes (4.5, 6.5, 8 and 10 mm diameters), with the following ratios between the diameter and the plate width: 0.15, 0.216, 0.266 and 0.33.

Tensile tests were performed under pseudo static load, under a displacement control, with a constant speed (0.5 mm/min) using a hydraulic INSTRON 8501 testing machine. Thermal images were acquired using a thermocamera FLIR SC3000, operating in the Long Wave Infrared (LWIR) band with wavelength range 8-9 μm, with a 20x15 degree FOV lens (spatial resolution 1.1 mrad) and a 20 mK thermal resolution. The frame rate was 1 frame/s. Figure 1 shows the enlarged thermal images for the different specimens and the thermal scale (e.g. ambient temperature 22°C in the last one). The figure also shows the four positions of the measuring points (from 1 to 4 going away from the hole); two other points were located on the central axis at a sufficient distance from the hole and from the grips so that the stress concentration factor could be neglected. Figure 2 shows the series of the specimens after the tests.

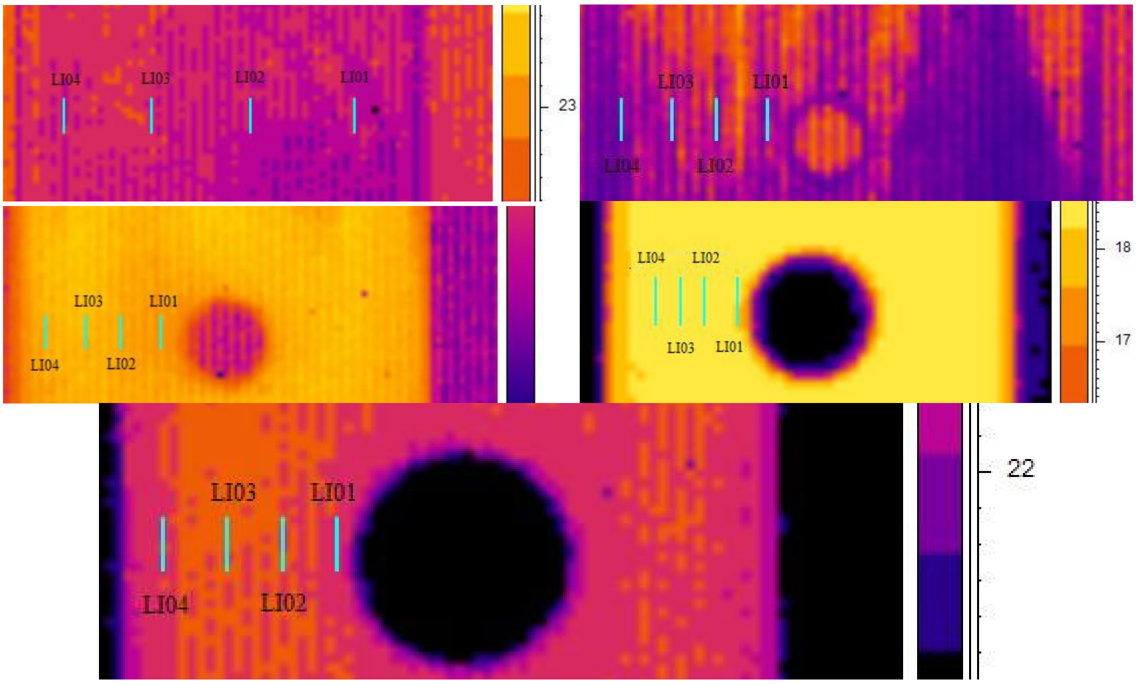


Figure 1. Thermal images with the spot position for the different hole diameters and the temperature scale (last image)

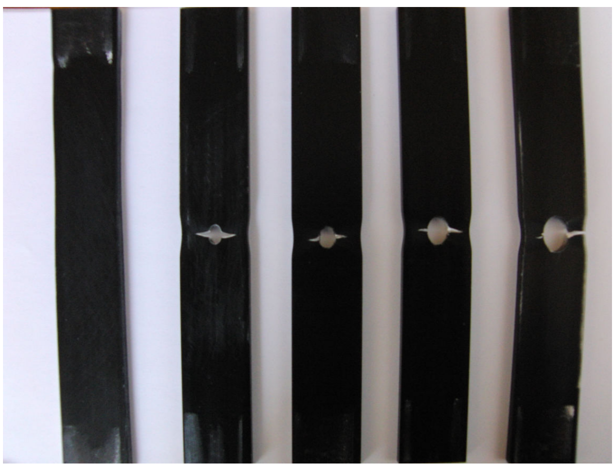


Figure 2. Specimens after the tests

RESULTS

The series of tensile trials confirmed the thermo-elastic behaviour in a first phase, totally elastic, with the thermal variation showing a linear decrease proportional to the applied stress. In the second phase, even if below the yield, the thermal decrease deviates from linearity as a result of the first local plasticization of the material, changing slope and becoming positive then, in the complete plastic phase. The results highlight the fact that, even in the traditionally static elastic phase, a variation from the theoretical behaviour is detectable in the static field using thermoelastic techniques.

As an example of the qualitative behaviour for all the tested specimens, in Figure 3 the sequence of temperatures along the cross line corresponding to the hole diameter is reported. The three images are related to the unloaded specimen (reference image), the elastic (applied load 2.26 kN, time 40 s) and the plastic phase (applied load 3.5kN, time 886s), respectively. Notably, the temperature is almost constant in the first image (stress null along the line), while in the second image it is lower near the hole edge (the thermoelastic effect is more remarkable due to the higher tensile stress). Finally, the last image shows a thermal increment near the hole (already in the plastic phase) and a thermal decrease far from the hole edge (tensile elastic stress still active). The sequence defines the transfer of the plasticization from the edge of the hole to that of the plate.

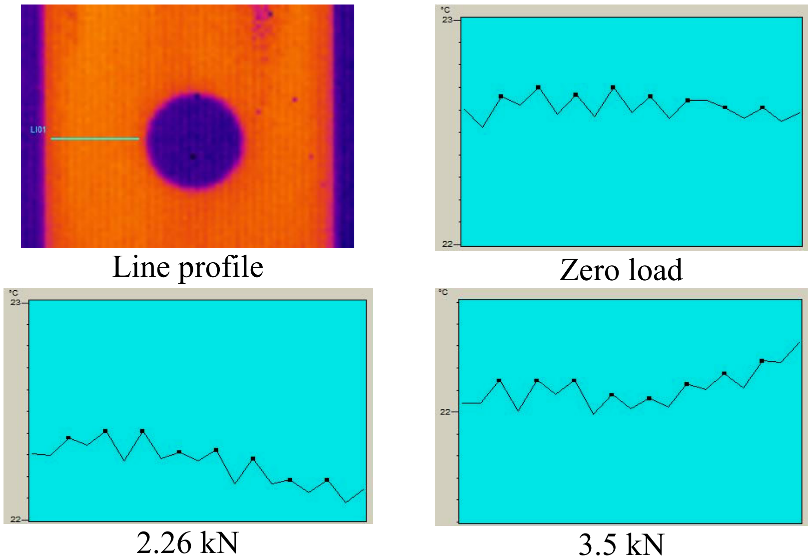
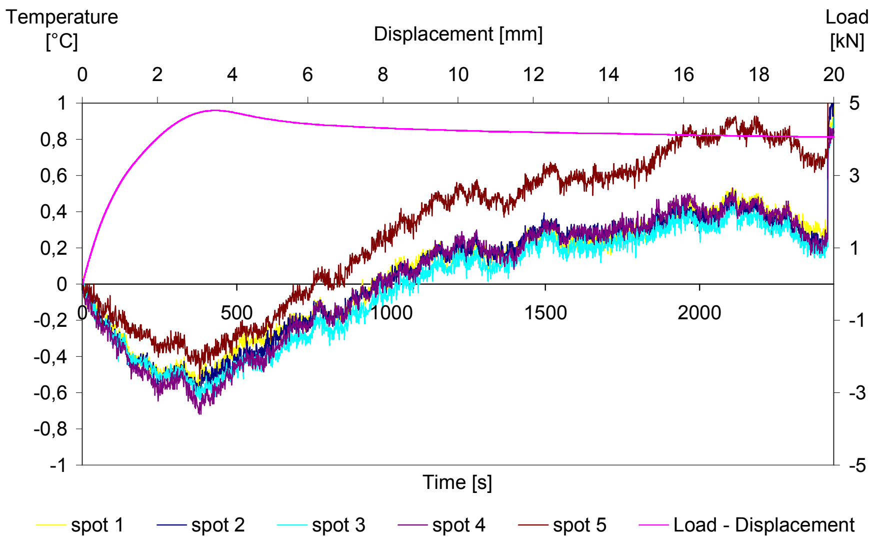
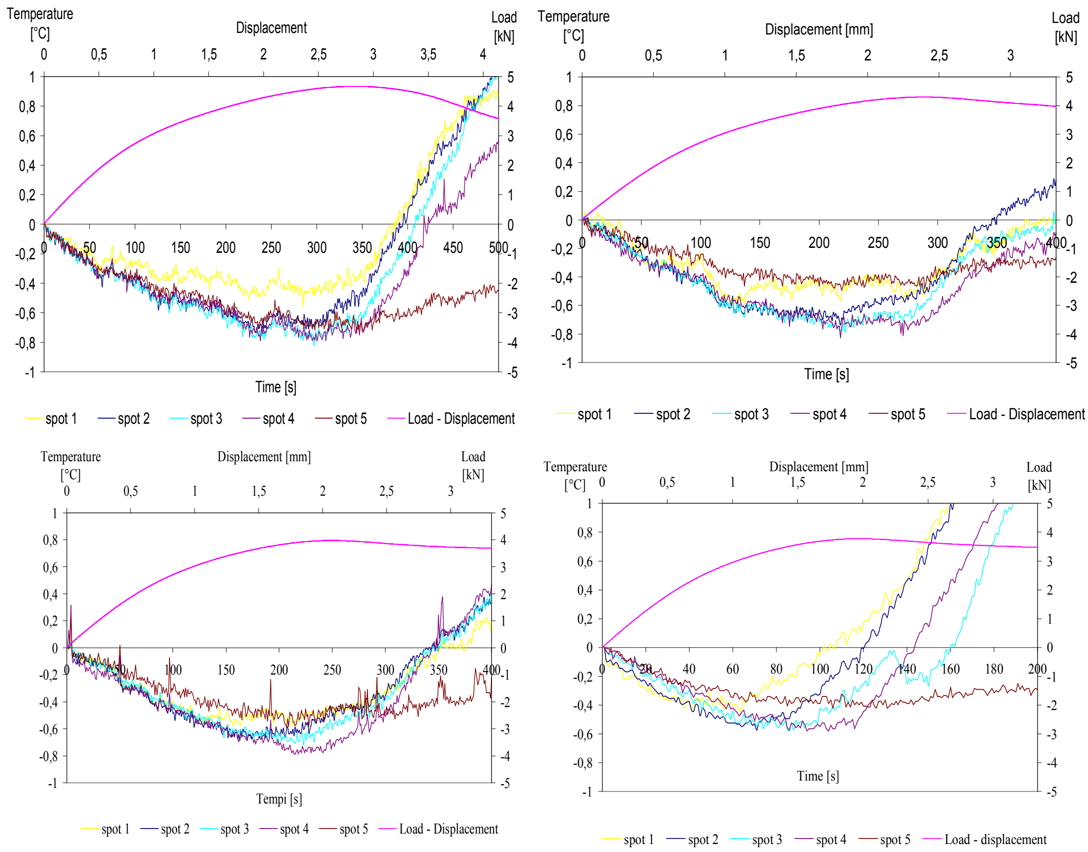


Figure 3. Sequence of temperatures along the cross line of the hole diameter.

Figures 4 to 8 show the thermal variations and the applied load for each measuring point as a function of the displacement. Moreover, the load values in which the slope changes and also the value in which the curve reaches the minimum, were defined on the curve. The minimum is correlated with the yield of the material. The slope change, following the above mentioned definition, could be linked to a value stress related to the fatigue limit, revealing the first heating effects due to the micro-plasticization.



Figures 4. Thermal variation of the spots in the unnotched specimen.



Figures 5 to 8. Thermal variation of the spots in the specimens with 4.5mm, 6.5mm, 8mm and 10mm hole diameter respectively.

Table 1 reports the distance from the hole edge for each spot and the corresponding value of the load at the end of the elastic limit (EL) and at the yield (YL). The position of the spots, difficultly located with precision during the thermal acquisition, has been exactly calculated using image processing techniques. The relative distance column is the ratio between the distance and the width of the half net cross section.

Table 1. Position of the spots in the specimens and thermally defined loads

Hole (mm)	Spot No.	Distance (mm)	Relative distance	EL (kN)	YL (kN)
0	1-4			4,10	4,80
4,5	1	1,60	0,10	2,00	4,55
4,5	2	5,10	0,32	2,20	4,55
4,5	3	8,00	0,49	3,34	4,60
4,5	4	11,50	0,71	3,44	4,60
4,5	5			4,20	4,80
6,5	1	0,90	0,05	1,80	4,28
6,5	2	4,10	0,24	2,98	4,05
6,5	3	7,10	0,42	3,22	4,05
6,5	4	10,70	0,64	3,67	4,28
6,5	5			3,69	4,28
8	1	1,50	0,09	2,40	3,90
8	2	3,90	0,24	3,00	3,55
8	3	6,50	0,40	3,40	3,90
8	4	9,10	0,56	3,70	3,97
8	5			3,87	3,90
10	1	0,90	0,06	1,92	3,07
10	2	3,40	0,22	2,73	3,23
10	3	5,60	0,36	3,08	3,54
10	4	7,60	0,49	3,20	3,73
10	5			3,20	3,75

It is possible to note how the corresponding load increases moving away from the hole edge, according to the stress concentration theory. Figure 9 shows the value of the load concentration factor (defined as a ratio between the load corresponding to the elastic limit far from the notch and that one in the spot) as a function of the relative distance from the hole edge.

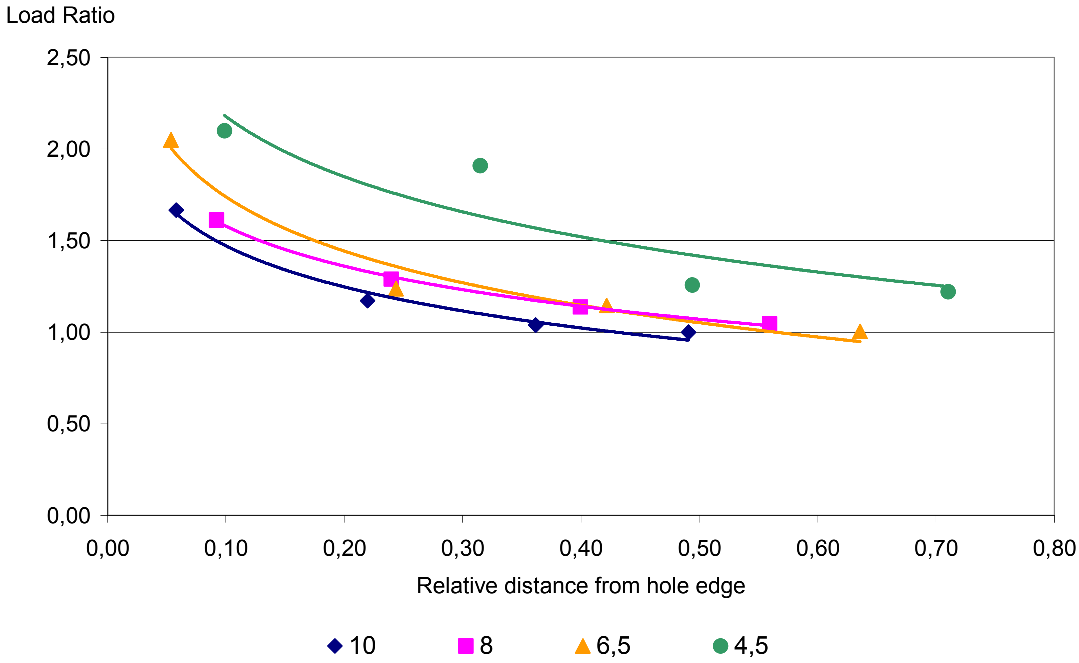


Figure 9. Load ratios for the specimens with 4.5mm, 6.5mm, 8mm and 10mm hole diameter respectively as a function of the relative distance.

CONCLUSIONS

The authors have confirmed that the static test, coupled with the thermographic analysis, for plastic materials also, can give reliable information about the elastic limit. The methodology was applied to plastics which normally present problems in the definition of that parameter. The thermoelastic effect (proportional to the stress in the totally elastic phase), deviating from the linearity, points out the beginning of the local plasticization.

Tests performed on PVC specimens with central holes of different diameters demonstrate that the variation of the stress near the hole is remarkable and could give useful information to a designer about the more critical points and about the local overload. Additionally, thermal behaviour makes it possible to follow the plasticization paths. In fact, the position of the totally elastic limits, have to be considered as the first crack initiation; then, following these points, moving from the hole edge to the plate boundary, the plasticization paths could be revealed.

In any case, the methodology has to be more deeply investigated. The authors consider this paper as the first step to define the endurance parameters and to link the elastic limits to the stress concentration factors. Future research will be performed with a higher geometric and thermal definition. Test will be performed under a load control, the authors considering it more reliable for this purpose. In order to verify the linking between the end of the elastic phase and the fatigue parameters, future studies will include a comparison between traditional testing methods and thermal analysis.

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