AUTOMATION OF THERMAL PAINTS ANALYSIS FOR TEMPERATURE MEASUREMENT OF ENGINE COMPONENTS

R. Andral
SAFRAN - TURBOMECA, France
Office National d'Etudes et de Recherches Aérospatiales (ONERA), France

C. Lempereur, H. Buchet
Office National d'Etudes et de Recherches Aérospatiales (ONERA), France

J.Y. Prudhomme
SAFRAN - TURBOMECA, France

1. Abstract

This article presents an automation method to analyze the tests performed on engine components with thermal indicating paints. These coatings change color with temperature and give a permanent visual record of the peak temperatures. The implementation of a 3D scanner and the development of specific image processing techniques enable to make the analysis quicker, more accurate and consistent than former manual interpretation. The expected result consists in three-dimensional surface temperature maps which are ready for input in thermal models.

2. Introduction

1.1 Context

Turbomeca (Safran group), as other aeronautical manufacturers, need to know the surface temperatures of gas turbine components with accuracy. Calculated in a theoretical way by numerical models, they are also measured directly on the engine components during dedicated tests. These measurements are essential because they allow to validate or adjust thermal models. In addition, they inform over the life span of the components under normal operation and ensure manufacturers of the respect of maximum temperatures allowed for each material. The current evolution in the field of aeronautical engines tends to increase the operating temperatures, to improve thermal efficiency and thus to reach higher powers.

1.2 Temperature measurements techniques

In this context, thermal paints constitute an effective means to measure the surface temperatures of engine components. They consist of different mineral pigments, binding agents and a solvent. They are sprayed on the surface of interest, with a thickness of about twenty micrometers. The color of these coatings changes according to the peak temperature. The physical phenomenon responsible for the changes of hue is irreversible.

The complexity of engine components does not enable numericians to foresee some peculiarities like high local temperature gradients, called hot points. Whereas, after a dedicated thermal paints test, once the engine is dismantled, the visual character of the technique allows immediate detection of hot points. Then a 3D map of the surface temperatures can be obtained.

There are other measurement techniques of surface temperatures, like optical pyrometry or thermocouples. Optical pyrometry is based on the fact that any material brought up to a given temperature emits a thermal radiation at its surface. The measurement of the emitted radiation does not require any mechanical contact, which is well adapted to the study of rotating components (turbine blades for example). However, its major drawback is to require specific knowledge of the emissivity of material. In our application, this parameter is generally badly known and induces measurement errors.

Thermocouples are widely used in industry for temperature point measurements. They are accurate, give real time measurement, and most of them can work up to 1700°C. On the other hand, they are limited by the complexity of their implementation inside an engine. In our application, this contact technique raises wiring problems, which are sometimes incompatible with the operation of the gas turbines. Nevertheless, they are used on some fixed components during thermal paints tests.

These two techniques give only point information and the data transfer remains a delicate point during tests. Thus, Turbomeca has chosen to use thermal indicating paints, mainly provided by Rolls-Royce. These coatings have been developed since the sixties. The manufacturers are still striving to improve the temperature range, the number of change points and the accuracy : measurements up to 1300°C are now possible.

3. Current implementation

After the dedicated “color” test, the engine is dismantled and components are ready for interpretation (Fig. 1). Examination of these tests is still done manually. The isotherms are marked out by hand on components, then reproduced on a paper sheet or photographed, to be transmitted in this rudimentary form to the numericians. Automation of the process will drastically reduce interpretation time, increase the number of detected isotherms and ensure a better accuracy. It will provide 3D surface temperature maps and make these data available as direct input into thermal models. It will also avoid the errors due to human color interpretation.

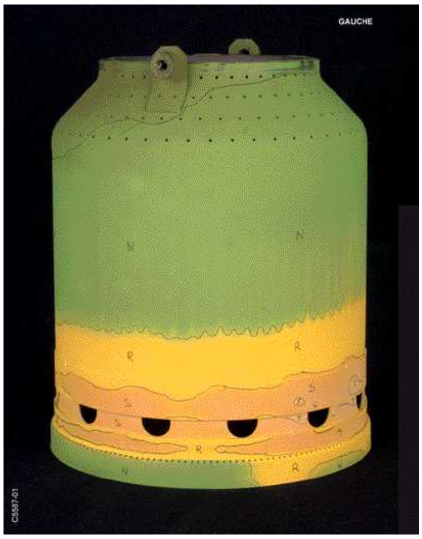

Fig. 1. Combustion chamber after test

The technique requires the preliminary realization of samples, heated to known temperatures, by step of 10°C. Rectangular coupons are painted with each thermal paint and heated in a laboratory kiln. The color to temperature correspondence is thus available (Fig. 2). Parallel to these tests, Turbomeca uses trapezoidal samples heated by Joule effect. The change in section generates temperature gradients along the piece and allows to continuously visualize the color evolution of the paint (Fig. 3 and Fig. 4), which facilitates further visual inspection.

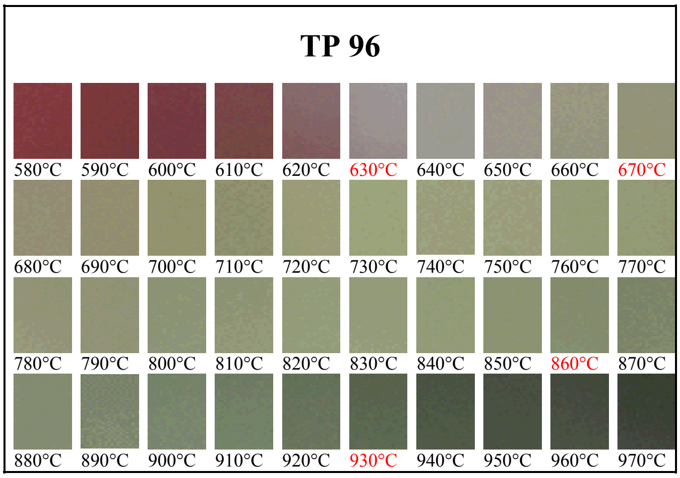

Fig. 2: Samples of TP96 thermal paint, heated by 10°C steps

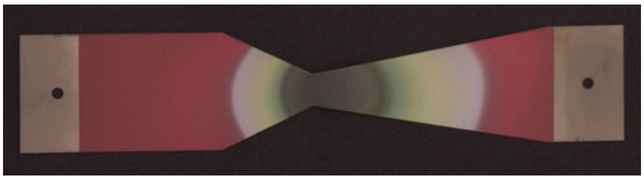

Fig. 3: Trapezoidal test piece used to visualize color changes (here TP96)

Fig. 4: Other thermal paints before (top) and after heating (bottom)

Although thermal paints mainly depend on peak temperatures, the color changes also depend on how long they are exposed to this temperature. This secondary dependence must not be overlooked. That is why the heating of samples respects a five-minute stage at the maximum temperature, corresponding to the duration of the maximum mode during engine tests. If the test is to be performed at different duration, a new set of samples respecting this exposure time must be prepared.

The number of isotherms detected by the human eyes varies according to thermal paints from four to eleven for those commonly used at Turbomeca.

During the same engine test, several types of thermal paints are used, each one presenting a different color changes set. The cross-checking of information allows to compensate the discrete character of color changes. For instance, the symmetry of rotating turbine blades can be exploited by using a different paint on each of them, thus increasing the final temperature map resolution.

4. Automation process

1.4 Temperature measurement from color images

1.4.1 Learning process

The set of painted coupons individually heated at 10°C increments in the effective range of the paint (Fig. 2) will be the basis of the learning process. RGB (Red Green Blue) images are acquired by a 3CCD camera and converted in Hue, Saturation, Luminance. This color space is usually preferred to RGB because it leads to a color representation independent of light intensity variation. Hue corresponds to the dominant wavelength of the color, and saturation refers to the amount of white added to the hue: pink is less saturated than red for instance. Luminance represents the brightness of the color, and is highly dependent on the lighting conditions.

The color spectrum of the image of each coupon is calculated in the (Hue, Saturation) plane, and attached to a temperature value. For a test duration of interest, a color-to-temperature data base is thus created for each type of paint.

The set of samples is also separated in main zones (red temperatures on Fig. 2) corresponding to visually detectable isotherms.

1.4.2 Matching process

The image of the engine component is then observed by the camera in similar conditions. The temperature recognition relies on color matching with the data base. A pixel-wise analysis of the current image is undertaken: the color spectrum is calculated on a 3x3 neighborhood and compared to the reference spectra contained in the data base. The pixel is labeled with the temperature corresponding to the highest match score.

1.4.3 Interpretation issues

This algorithm is straightforward, easy to implement and gives a temperature image of the object. Nevertheless, such a raw analysis may lead to surprising results.

The main problem comes from the fact that thermal paints exhibit sharp color-change points between which color hardly varies, or at least the variation is not detectable. For instance, the color spectra of TP96 show constant hue and saturation mean values (respectively 60 and 29) in the 780–850°C temperature range (Fig. 5). The paint is not discriminating there, at least with respect to the analysis method. In such regions, the match score can be as high for any of the involved temperatures, thus ending in noisy temperature maps. A preliminary "self-matching" performed on the data base enables to visualize the regions where this phenomenon occurs. A temperature range is assigned as a result, instead of a temperature value.

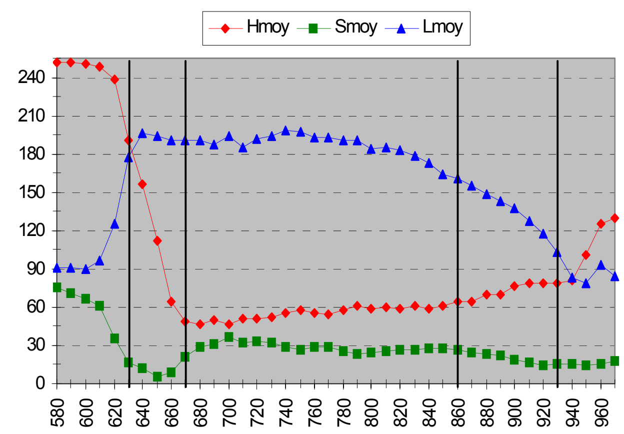

Fig. 5. Evolution of Hue, Saturation and Luminance according to temperature

If the locally reached temperature is missing from the data base, -being lower (or greater) than the minimum (or maximum) temperature of the samples- the matching process will nevertheless give a best score, which may be difficult to sort out as non-valid. Increasing the threshold on scores to discriminate between valid and non-valid ones is difficult to automate.

1.4.4 Global processing steps

Some more processing steps need to be performed before and after this color matching algorithm to ensure the temperature maps consistency.

A preliminary step consists in a supervised color segmentation of the components image. The operator points at a given pixel and the algorithm returns a cluster of "similar" neighboring pixels (Fig. 6). The edges of this cluster can be made very close to the isotherms a skilled operator would have drawn by hand, simply by adjusting the similarity threshold. This procedure is repeated so far as to cover the whole image.

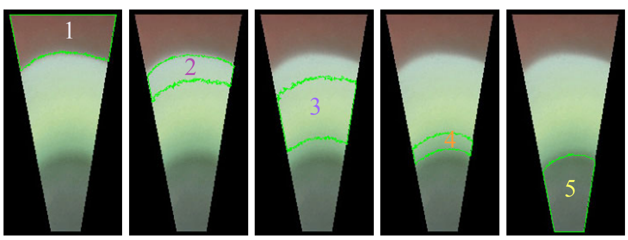

Fig. 6. Supervised color segmentation

The isotherms marking procedure thus becomes much quicker and more accurate, while fitting the former manual method. In the same time, the regions are labeled in terms of temperature range (i.e.: area n°1 corresponds to 580–630°C range); the color matching algorithm is made faster and more reliable by this preliminary classification.

The temperature map must then be completed by a map indicating the measurement accuracy. On the one hand, the “visible” isotherms correspond to accurate temperature values, while on the other hand, some points are assigned a rather large temperature range. This lack of information is compensated by a combined use of paints with different temperature change points.

The last examination will have to be made by thermicians in order to check the consistency of the 3D surface temperature map.

1.4.5 Results and discussion

The temperature map (Fig. 7) of the test piece coated with the same paint as the samples (Fig. 2) is calculated according to the previous algorithm after a color segmentation.

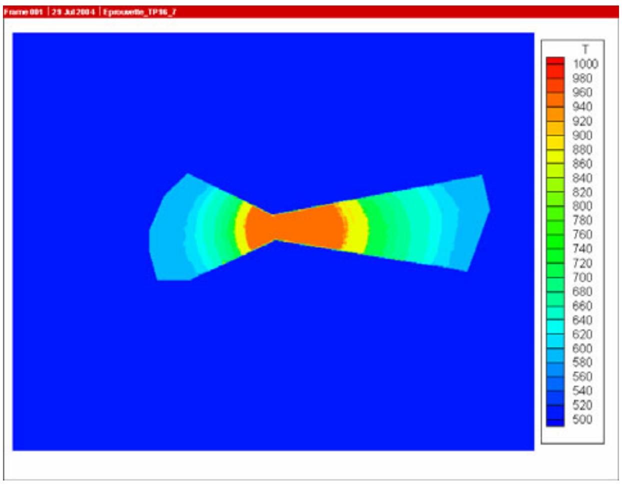

Fig. 7. Temperature map of the test piece

The temperature increases while the cross section decreases, owing to the Joule effect. The outer parts of the piece correspond to temperatures lower than 580°C while the central part is hotter than 970°C; these areas cannot not be measured in this case because the data base is not complete. Moreover, at high temperatures, the paint glaze makes visualization difficult: specific attention has to be paid to lighting conditions. In the above mentioned range (780–850°C) where the paint color is measured as constant, the temperature is determined as belonging to this range. Elsewhere the temperature profile is roughly discriminating 10°C increments (Fig. 8).

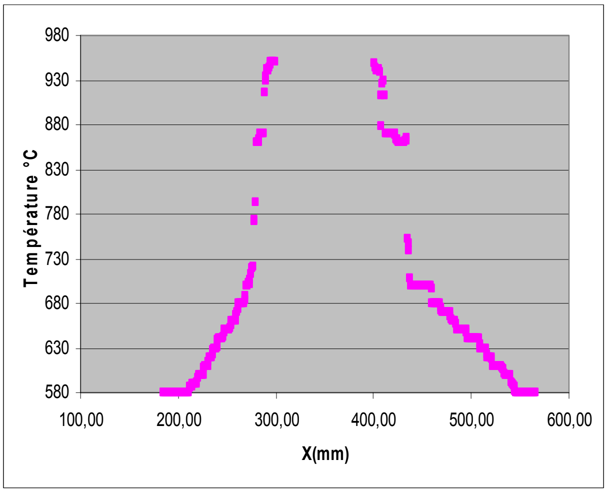

Fig. 8. Temperature profile along the test piece

This example demonstrates how the resolution of temperature measurement can be improved compared with a visual inspection which would only give four temperature values in this case (630°C, 670°C, 860°C, 930°C). However, the real accuracy is not yet available: pyrometric measurements performed during the heating of the test piece are being undertaken at Turbomeca and will be of great help for a full validation of the measurement process.

1.5 Three-dimensional temperature maps

The color to temperature algorithm which has been presented above has now to be integrated into a full process to yield three dimensional maps of surface temperature.

1.5.1 3D digitization process

To achieve so, a 3D scanner has been implemented at Turbomeca (Fig. 9). This device is controlled by a computer via a dedicated software. The object is scanned by a laser sheet which is swept across the field of view by a mirror, accurately rotated by a galvanometer. The laser light reflected on the surface of the object is acquired by a CCD camera. The whole field of view is captured in 2.5 s. A color image of the area is also acquired by the same camera after the scan, by way of a rotary filter holder which gives three successive (R,G,B) planes.

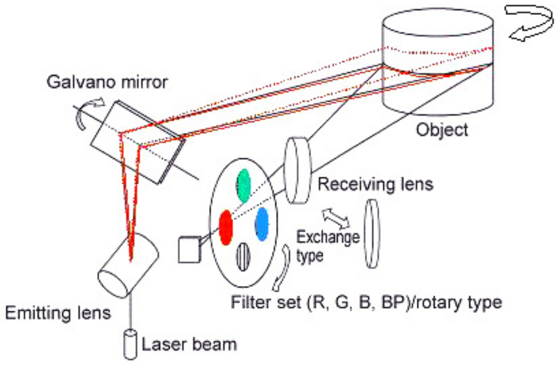

Fig. 9. Principle of non-contact 3D digitization (Minolta 3D scanner)

If one view is not sufficient to describe the whole object, scanning it from all sides is made easy: the piece is placed on a rotating stage and successively scanned at a few degree increments. A polygonal mesh is then created by merging all the views, to define the outer surface of the object (Fig. 10). The digitization volume can range from $110 \times 80 \times 40\ mm^3$ to $1200 \times 900 \times 750\ mm^3$, with an accuracy of roughly 0.1 mm.

1.5.2 Work in progress

The next step of automation will consist in adapting the previous matching algorithm to the color images obtained by the digitizer and to map the temperature information on the component mesh.

Visualization and lighting of 3D surfaces are difficult issues which may affect the temperature recognition process. Although the color matching is performed on hue and saturation parameters, a dependence on lighting variations exists. The illumination of the area must remain as uniform as possible and stable with time. Up to now, the white light source is aligned with the optical axis of the camera. The angle α between the normal to a facet and the visualization direction at this point also affects the perception of hue (Fig. 11). Specific tests on the rotary stage have shown that beyond $\pm 30°$ the color matching process may be distorted. Moreover, the apparent surface of the facet decreases with α. This angle can be calculated from the files describing the mesh and the point of view. It will be used as a parameter of the color to temperature mapping. Prior to affecting a temperature to an object point, the facets it belongs to must be classified according to angle α. The temperatures corresponding to the smallest angles will have a higher weight in the final measurement. A 3D mesh is thus obtained, where each facet (or vertex) is given a temperature value.

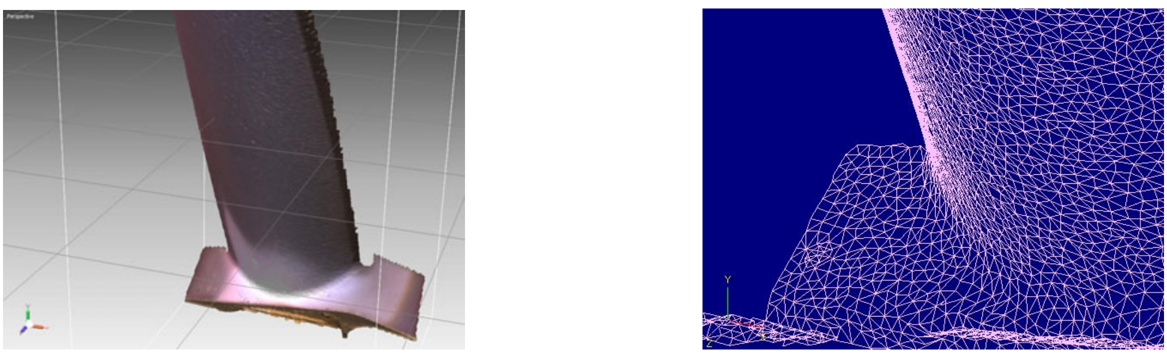

Fig. 10: Polygonal mesh of a blade and zoom on the blade root

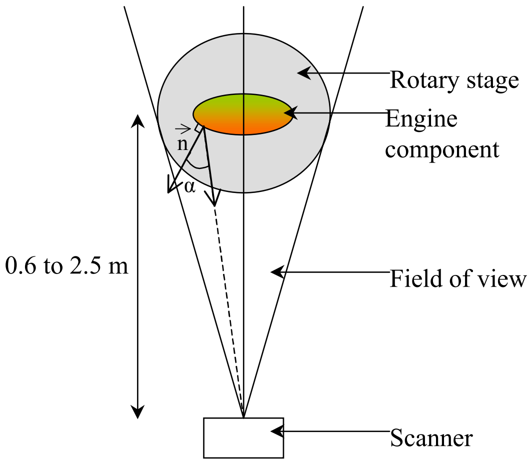

Fig. 11. Field of view and angle α definition

1.6 Limitations

Although automation is expected to make analysis easier, the appreciation of a skilled operator who brings an irreplaceable expertise will remain necessary in some cases. Actually, several factors may affect the measurement process: the coating color may be polluted by unburned gases or lubrication oil deposit, the upper layer may be locally eroded. Moreover, the oxygen concentration in gases during the thermal test can modify the chemical reactions responsible for the color changes.

5. Conclusion and outlook

The automation of thermal paints analysis has been undertaken on the basis of a 3D scanner coupled with specific color recognition algorithms. The feasibility of obtaining 3D temperature maps has been demonstrated in this laboratory context. There are still many factors to investigate to make the technique efficient in an industrial environment: lighting and viewing conditions particularly on large 3D components, interpretation of degraded coatings, interfacing to numerical models.

The duration of a whole color test cycle (painting of pieces, assembly, thermal test, disassembly and analysis) can reach up to five or six weeks on complex engines. In spite of a high development cost, these tests remain systematic because of the irreplaceable information they deliver. The analysis automation will partly reduce these time and cost factors while increasing resolution and accuracy.

Other types of coatings with photoluminescent properties have just started being investigated. They could be an interesting alternative to the colored thermal paints as they would give a continuous intensity to temperature relationship, and offer a larger temperature range, up to 1500°C.

6. Acknowledgments

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7. References

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