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# Discrimination Between Over-Thickness and Delamination of Thermal Barrier Coatings by Apparent Thermal Effusivity Thermographic Technique

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**When the delamination extent of thermal barrier coatings (TBC) is over a sufficiently large area to assess the adhesion of coatings, Pulse thermography (PT) is an effective technique, but often the distinction between delamination and TBC over-thickness is very difficult to determine. In this work, a recently developed algorithm based on apparent thermal effusivity has been applied to automatically distinguish between delamination and over-thickness during the inspection of a serviced gas turbine TBC-coated vane.**

**Keywords** NDE&T, pulse thermography, thermal barrier coating, thermal effusivity

## 1. Introduction

TBCs are widely applied for protecting hot path components of gas turbines from high-temperature combustion gases (Ref 1, 2). Typical TBCs are metal-ceramic multilayers structures made up of a yttria partially stabilized zirconia (7-8 wt.% $Y_2O_3 + ZrO_2$) layer deposited either by air plasma spray or electron beam-physical vapor deposition on a high-temperature oxidation/corrosion resistant metallic bond coat (BC) (Ref 1, 2). The refractory ceramic porous layer can reduce the temperature of the base metal by 30-100 °C, depending on the thickness and on specific microstructural properties of the coating.

During engine operation, several high temperature cycle-dependent phenomena take place within the TBC system determining its lifetime. In particular, high temperatures promote the sintering of the TBC and the progressive formation of a thermally grown oxide (TGO) layer at the interface between the BC and the TBC which contributes to the failure by spallation of the top coat.

In fact, since the TGO grows at high temperatures in nearly stress-free conditions due to the thermal expansion mismatch among the TGO, TBC, and BC, at room temperature relevant residual stresses are induced close to the interface within both the TGO and the TBC. The increase in the TGO thickness promotes the change of the sign of residual stresses within the TBC (from compressive to tensile, correlating to roughness valleys), allowing microcracks previously enucleated within the TBC correlating to roughness peaks to propagate and to coalesce together along the BC-TBC interface. Moreover, crack propagation becomes more favorable because the formation of chemical bonding between splats induced by sintering phenomena allows cracks to propagate through different grains without being deflected, making the TBC fragile (Ref 3, 4).

When the delamination extent of the TBC is over a sufficiently large area (usually a few squared millimeters, the size being related to the TBC thickness, to the TBC thermal diffusivity and to the air gap of the delamination itself), Pulse thermography (PT) is an effective nondestructive technique (NDT) to assess the adhesion of coatings such as thermal barrier coatings (TBC). As a matter of fact, this technique is used today as a quality control technique, especially during the development of the deposition procedure for complex-shaped components or for in-field coating inspection of serviced components (Ref 5, 6).

When serviced components require inspection, difficulties in the interpretation of the thermographic sequences can arise from the presence of stains, rough regions, eroded areas, over-thickness of the coating and, generally speaking, from any uneven optical property of the surface.

Many algorithms such as pulse phase thermography (Ref 7), log-log fitting (Ref 8), and principal components analysis (Ref 9) are effective in suppressing the effect of surface features from the sequences of thermographic images. In fact, the visibility of delamination defects can be enhanced when one of these algorithms is applied to the temperature time profiles extracted from the sequence of thermographic images.

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Unfortunately, the same situation does not apply to coating over-thickness. For coating thickness changes which are not regarded as defects, the effect on the temperature behavior is not simply multiplicative, and the previously mentioned algorithms are not helpful. When other nondestructive techniques (e.g., Eddy Currents) cannot be applied for estimating coating thickness owing to the complex geometry of the component (a typical example is the transition region between blade airfoil and platform) it is not possible to discriminate between over-thickness and delamination.

In this work, the recently developed algorithm based on the apparent thermal effusivity (Ref 10) has been applied to distinguish between delamination and over-thickness during the inspection of a serviced gas turbine TBC-coated vane. While in the previous work, due to some limitations in the experimental setup (i.e., too long pulse duration and the absence of thin blackening graphite layer on the TBC), a simplified less effective approach was applied to IR sequences, in the present work all the limitations have been successfully removed.

## 2. Apparent Thermal Effusivity

### 2.1 Theoretical Remarks

When sufficiently large, diffuse cracking at the interface between BC and TBC evolves toward macroscopic delamination. PT is a rapid and effective NDT tool to detect the presence of coating delamination by monitoring the evolution of the surface temperature during a thermal transient usually induced by a flash lamp system (Ref 5).

Even if a simple time resolved analysis of the TBC surface temperature is sufficient to clearly detect delamination as those areas with a slower cooling rate with respect to those areas assumed to be sound, there are some cases where the TBC over-thickness yields indications similar to a defect. In order to automatically distinguish between delamination and significant over-thickness, the apparent thermal effusivity algorithm has been developed recently (Ref 10).

As explained more in detail elsewhere, the apparent effusivity is a parameter that can easily be obtained for each pixel from a sequence of infrared images as (Ref 10):

$$e_{\text{app}}(L,t) = \frac{1}{T(L,t)\sqrt{t}}, \qquad \text{(Eq 1)}$$

where $T$, $t$, and $L$ are the surface temperature, the time after the flash, and the TBC thickness, respectively. Since for a two-layer semi-infinite sample the surface temperature after a spatially uniform heating Dirac flash can be expressed as (Ref 11):

$$T(L,t) = \frac{W}{e_c\sqrt{\pi t}}\left(1 + 2\sum_{n=1}^{+\infty}(-\Gamma)^n e^{-\frac{n^2L^2}{\alpha_c t}}\right) \qquad \text{(Eq 2)}$$

A dilation or compression of the time axis, according to the scale factor $a = 1/(1+\Delta L/L)^2$, corresponds to a thickness variation $\Delta L$ if the other parameters are untouched, meaning that:

$$e_{\text{app}}(L+\Delta L,t) = e_{\text{app}}(L,at) \qquad \text{(Eq 3)}$$

When the ln-ln representation is adopted where the ln operator indicates the natural logarithm, the effect of $\Delta L$ is a simple translation along the $\ln(t)$ axis without changing the monotonic nature of $e_{\text{app}}$.

$$\ln\big(e_{\text{app}}(L+\Delta L,\ln(t))\big) = \ln\big(e_{\text{app}}(L,\ln(t)+\ln(a))\big) \qquad \text{(Eq 4)}$$

On the contrary, the presence of an adhesion defect causes the appearance of a minimum and therefore a distortion of the $e_{\text{app}}$ curve, as shown in Fig. 1. Thus, to distinguish adhesion anomalies from accepted coating variations, the initial value of $e_{\text{app}}$ can be fixed as a threshold between delamination and over-thickness.

The main limitation of this technique is related to the ratio of thermal effusivity of coating and substrate: the appearance of a minimum when a delimitation is present at the interface between coating and substrate takes place only if the thermal effusivity of the substrate is equal or higher then that of the coating. Fortunately this condition is often met in real-coated components.

### 2.2 Experimental Procedure

**2.2.1 The Sample and the Component.** The apparent thermal effusivity algorithm has been applied to a reference sample and to a serviced gas turbine vane coated by an APS TBC system. The reference sample consisted of a metallic substrate coated by an high-velocity oxy-fuel (HVOF) metallic coating with a delamination defect in the middle of the sample. On half of the sample, the coating thickness is nominally double in respect to the other half. The adhesion defect is located at the interface below the transition region between the thin and thick coating, as shown in Fig. 2.

Figure 3 shows the serviced vane exhibiting optical nonuniform features. The TBC thickness has been

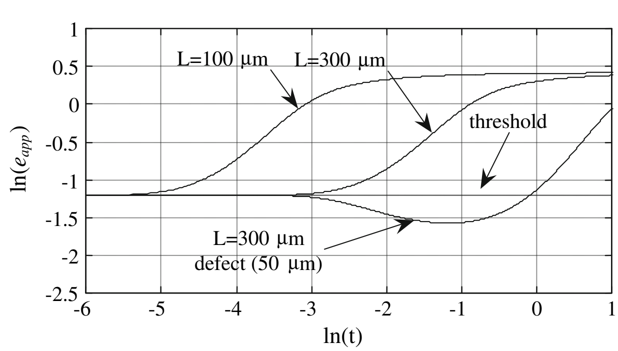


**Fig. 1** Influence of a thickness variation (from 100 to 300 μm) and an adhesion defect (50 μm of air under a 300 μm coating) on the apparent effusivity curve in ln-ln representation, as expected by simulating both occurrences. In the case of a thickness variation, just a translation of the curve is observed while a minimum arises when a delamination defect is present

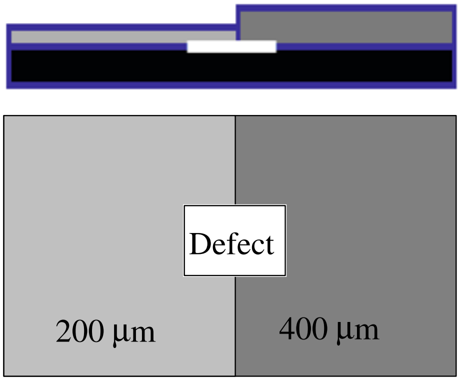


**Fig. 2** Sketch of the reference-coated sample with an adhesion defect and two regions with different coating thickness

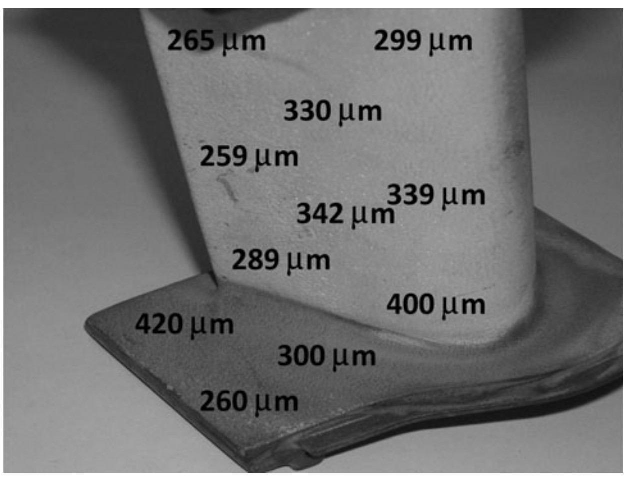


**Fig. 3** Picture of the serviced vane. Due to operation, TBC surface is characterized by different gray levels. TBC thickness measured by EC probe is also reported

nondestructively measured by an Eddy Current probe (Krautkramer Branson layer thickness meter Data Met) where the probe size was compatible with the vane geometry. Indicative TBC thickness values are indicated in Fig. 3 as well. After a preliminary integrity assessment carried out by PT, an indication along the transition between the platform and the foil was detected. The infrared image of the vane taken 0.3 s after the flash can be seen in Fig. 4. A sample with a TBC delamination is also visible in the image. Neither time resolved nor Fourier analyses were able to clearly indicate whether the hot identified region was a delamination or an over-thickness because the very small curvature radius of the vane in that area of the TBC thickness measurement by EC was not allowed.

**2.2.2 Experimental Setup.** A 1064 nm wavelength Nd:YAG laser (Theta Industries Inc., Port Washington, NY) generating pulses of about 0.8 ms was used as a heating source. The energy and the diameter of the

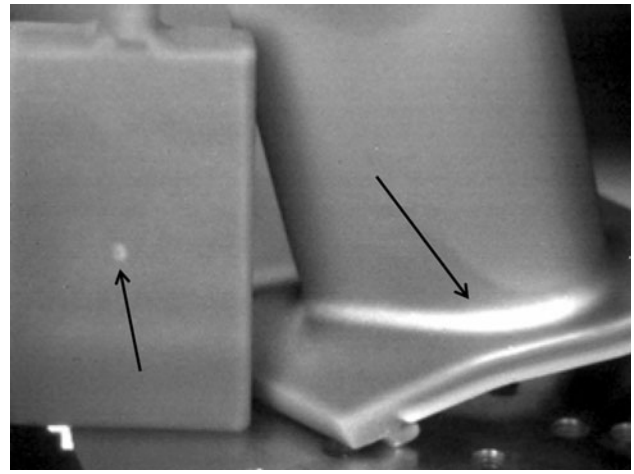

**Fig. 4** Infrared image of both the vane and a TBC-coated sample with an artificial reference delamination. The indication along the transition zone between platform and foil is clearly visible as a hot spot (similarly to the artificial spot shaped defect in the TBC-coated sample) 0.3 s after a flash emitted by two flash lamps, as pointed out by the *arrow*

heating shots were fixed roughly equal to 8 J and 50 mm, respectively.

A snapshot focal plane array IR camera sensitive in the range of 7-10 μm (Jade II LW, CEDIP Infrared Systems, Croissy-Beaubourg, France) was used to monitor the temperature transient of the sample surface at frame rates of 1000 and 150 Hz for the metallic coating and the TBC, respectively. The noise equivalent temperature difference (NETD) of the infrared camera is 30 mK. Typical minimum temperature difference between sound and delamination should be of the order of about 150 mK. The typical order of magnitude of the energy density heating the component is $10^4$ J/m$^2$. A picture of the experimental setup is shown in Fig. 5. Owing to the TBC translucency, a thin layer of colloidal graphite was painted on the front sample surface in order to make the TBC opaque to the Nd:YAG laser radiation.

### 2.3 Results and Discussion

The real capabilities of the proposed technique to discriminate between over-thickness and delamination were assessed by testing the metallic sample coated with a metallic coating. Figure 6(a) shows in ln-ln representation the experimental $e_{app}$ curves as a function of time for four areas corresponding to sound thin and thick and defected thin and thick coating, respectively. Each curve refers to the apparent effusivity value averaged on 25 pixels. As expected, $e_{app}$ curves referring to sound areas do not show any minimum but only a shift caused by the different coating thicknesses. On the contrary, $e_{app}$ curves for defected areas show a minimum which is shifted analogously to the two previous curves. An alternative way of representing reduced data consists of an image where, in correspondence to each pixel of the infrared image, the value of the time corresponding to the minimum of the

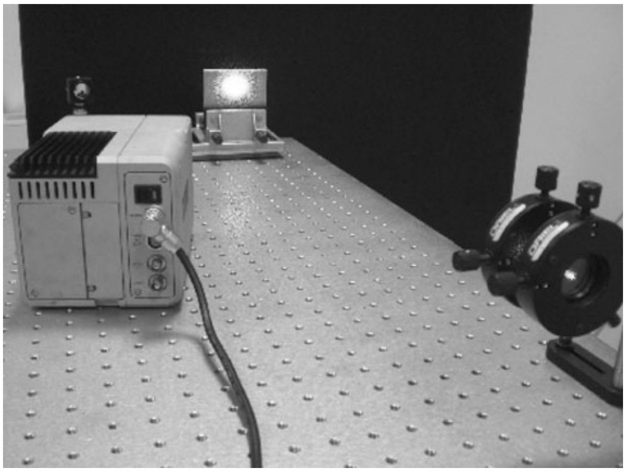

**Fig. 5** Picture of the experimental setup. The pointing laser beam is visible on the sample surface. The infrared camera monitors the surface temperature vs. time after the heating laser flash

$e_{app}$ curve is indicated (for sound and defected regions, the minimum occurs at the initial and at longer times, respectively), as shown in Fig. 6(b). In particular, the round area corresponds to the area heated by the laser beam; the two roughly rectangular-shaped areas with two different values of time refer to the defect while no difference can be observed for sound areas having different coating thickness. The two different values of time corresponding to the minimum are caused by the different coating thickness over the defect.

After the good results obtained on the reference sample, the vane was inspected by the same procedure. Although Fig. 7(a) shows some shadings indicating candidate delaminations, the results of the proposed procedure (see Fig. 7b and c) do not show any delamination. A check performed by optical microscopy after sectioning the vane in different pieces confirmed that no delamination was present at the interface between the BC and the TBC and that a significant over-thickness was present all along the transition between the platform and the foil. In particular, the coating thickness in this area resulted in roughly 600 μm (see Fig. 8) which is almost double the thickness measured on the foil and on the platform.

For this demonstration activity, a laser was used to apply the apparent thermal effusivity algorithm without generating artefacts in the resulting curves or maps. A heating pulse shorter than 1 ms is required. In fact, as explained elsewhere, a longer pulse duration produces a fictitious minimum in the apparent thermal effusivity curve which invalidates the data reduction procedure in this powerful version, as it can be seen in Fig. 6(b) where a flash lamp with a pulse duration of 5 ms is used (Ref 10). In any case, a laser can be injected into a fiber for remote use or the laser source can be substituted by flash lamps with a pulse duration of 1 ms.

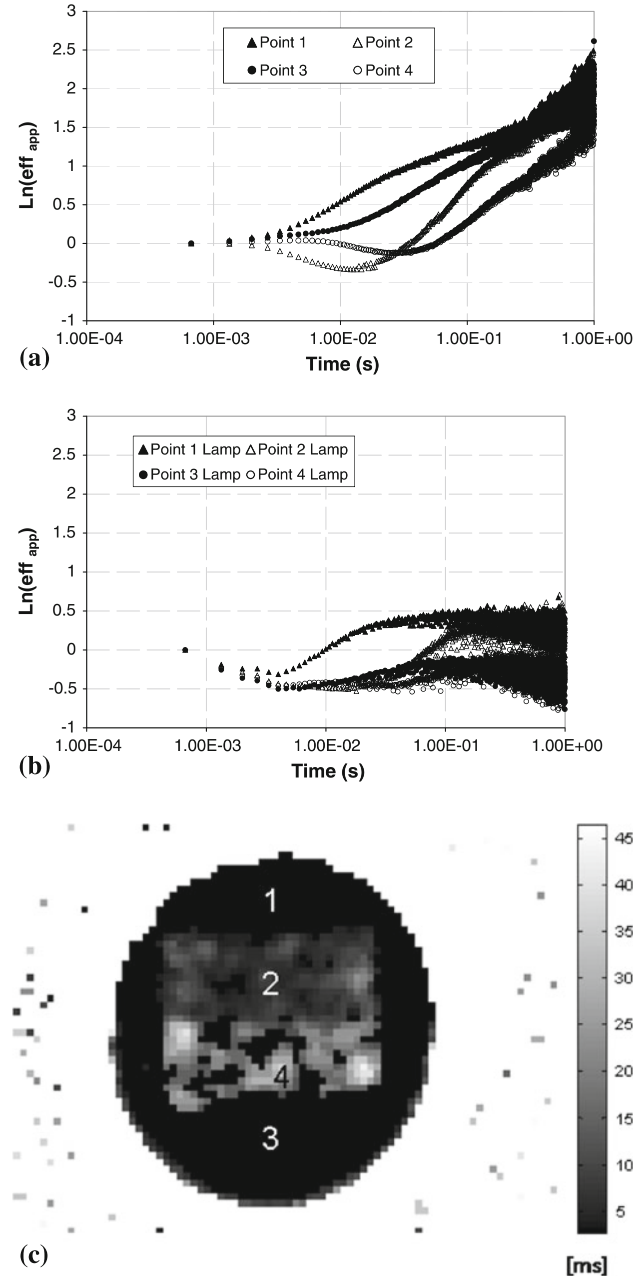


**Fig. 6** Reference sample. (a) $e_{app}$ curves in ln-ln representation for four areas (5 × 5 pixels) corresponding to sound thin (point 1) and thick (point 3) and defected thin (point 2) and defected thick (point 4) coating, respectively. (b) The same as (a) when a pulse duration of 5 ms is used. (c) Map of the times of occurrence of the minimum for the $e_{app}$ curves corresponding to the field of view of the IR camera. The only indication within the map concerns the delamination but not the two regions with different coating thickness

Concerning surface preparation, depending on the wavelength of the heating source, it is possible to avoid painting the TBC surface by a thin graphite layer prior to the testing activity.

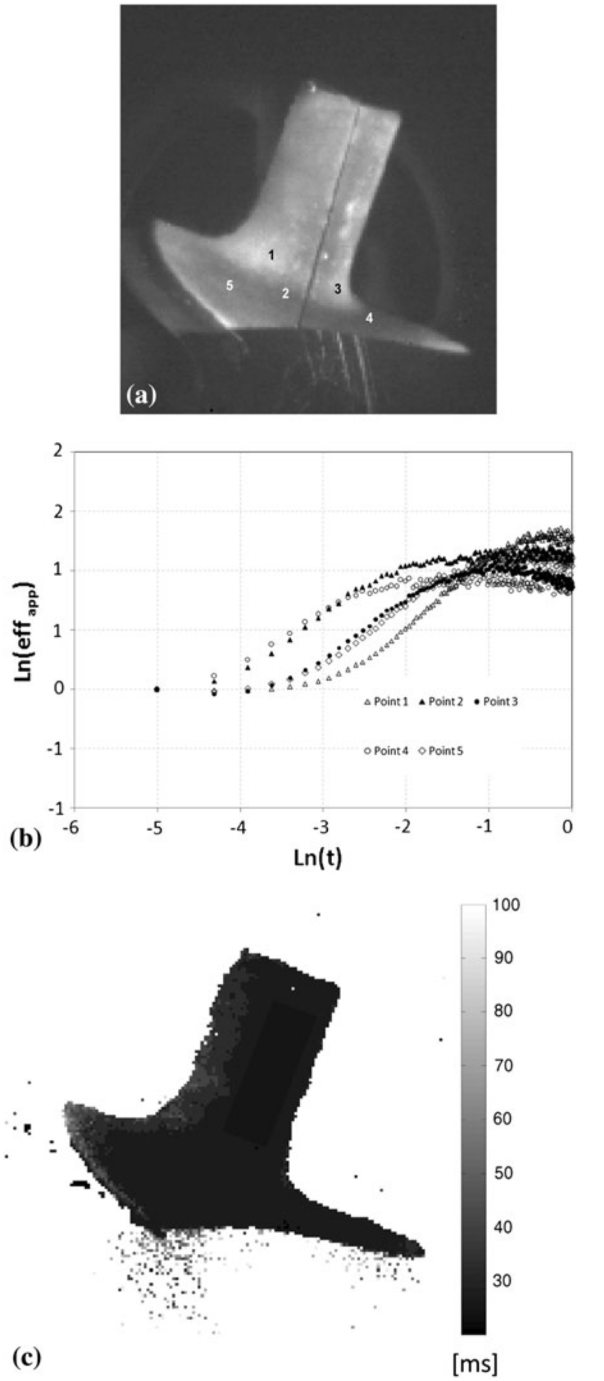


**Fig. 7** Vane. (a) Infrared image of the vane (67 ms after the flash) and the five areas ($5 \times 5$ pixels) considered for apparent effusivity curves reported in Fig. 7(b). (c) Map of the times of occurrence of the minimum for $e_{app}$ curves for the vane surface. No indications of delamination can be seen both in (b) and in (c)

## 3. Conclusions

The apparent thermal effusivity algorithm proved to be a powerful data reduction method of pulsed thermography

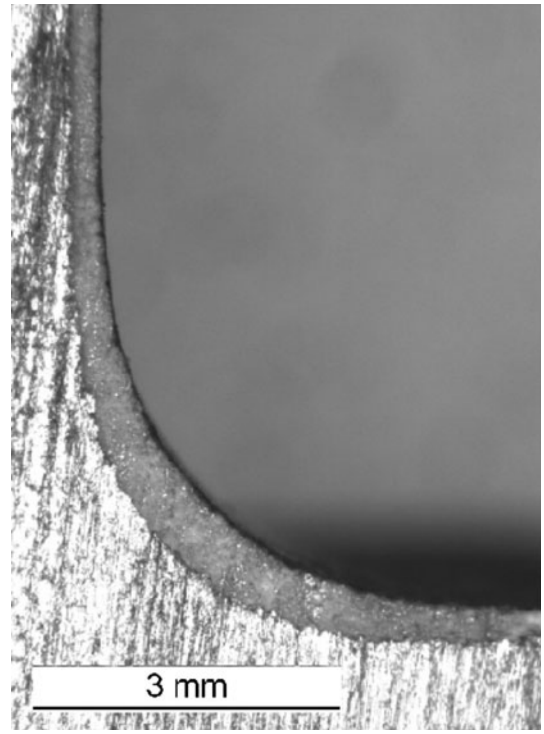


**Fig. 8** Vane. Section crossing the transition between platform and foil. The TBC over-thickness in correspondence of transition can be clearly observed

infrared sequences to discriminate coating adhesion defects from any other indication with particular attention to those defects caused by the coating over-thickness when a sufficiently short flash ($<1$ ms) is used.

A limitation that has to be taken into account is that the thermal effusivity of the substrate must be equal or higher then that of the coating. Fortunately, this condition is often met in real-coated components.

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