Inspection of HVOF-coated Pelton wheels using laser thermography

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Abstract

After a feasibility study for the NDT (Non Destructive Testing) of Pelton turbine with hard coating, EDF decided to go ahead with an industrialized version of the Photo-Thermal Camera (PTC) developed by Framatome-Intercontrôle. The PTC is a portable laser thermography system. Before, a demonstration of performance was leaded in order to determine:

- the settings of the PTC;
- the impact of the influential/essential parameters according FD CEN/TR 14748 approach.

A specific support for the PTC was manufactured in order to optimize the inspection duration and to allow co-activity during the outage. The first implementation was realized successfully on an EDF site.

1. Introduction

Among the many hydroelectric plants operated by the EDF Alps Production Unit, some facilities are distinguished by the use of turbine water from melting glaciers. This water, which contains a lot of sediment and mineral particles, causes a phenomenon of strong wear by abrasion of the Pelton turbines used in these installations, given their intensive use in run-of-river hydro power stations.

To improve operating performance of the wheels subject to wear, the EDF Alps Production Unit decided to experiment with HVOF (High Velocity Oxy-Fuel) coatings deposited by hypersonic flame on the Pelton wheel buckets. This technique, which had already been used by EDF on other components for years, makes it possible to deposit a very hard material (tungsten carbide 86%WC), which is therefore highly resistant to abrasion, with the best grip characteristics of the coating at a very fine thickness (around 300 µm).

New wheels coated using the HVOF procedure were fitted to a turbine in some "pilot" plants. The feedback from 10,000 hours' operation has already indicated a drastic improvement in the state of wear of the coatings and allows strong supposition that there could be a gain of a further 2 years of useful life compared with traditional coatings, see figure 1:

- HVOF-coated buckets have a very smooth surface with hardly any wear marks ;
- the coating is still present in practically all functional areas with little loss of thickness.

NDT by magnetic particle testing (MPI) carried out by the EDF maintenance teams is based on the search for the indication of a crack, caused by a phenomenon of magnetic AC flux leakage from the bucket that has been magnetised and sprayed with a developer containing fine ferro-magnetic particles. The HVOF anti-wear coating acts as a barrier against the phenomenon of flux leakage, see figure 2. The main consequence of this is a strong reduction in the sensitivity of detection, which is unacceptable in areas subject to high strain from fatigue. Failure to detect a crack several millimetres long during a periodic inspection could in fact lead to breakage and ejection of a bucket in service, which is unacceptable in terms of risk to property and people.

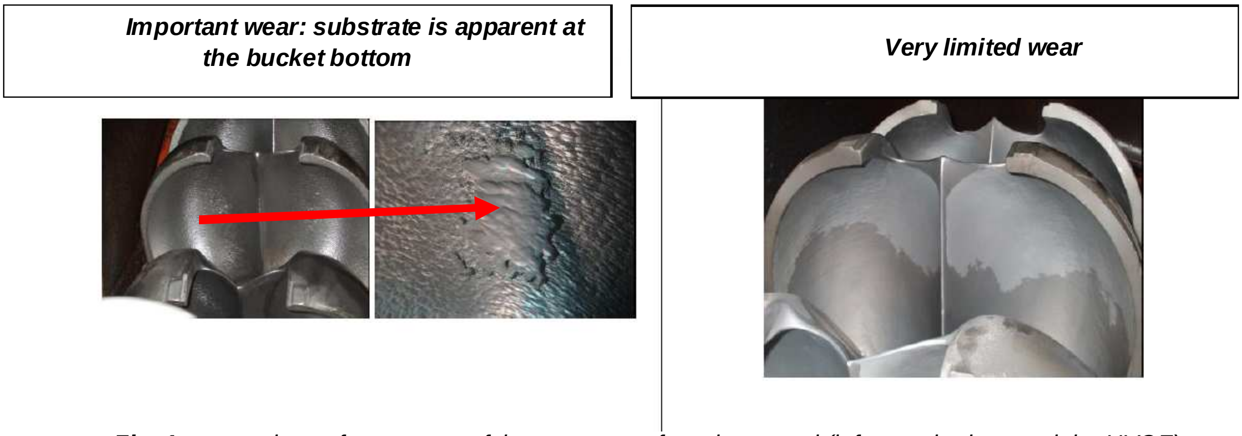
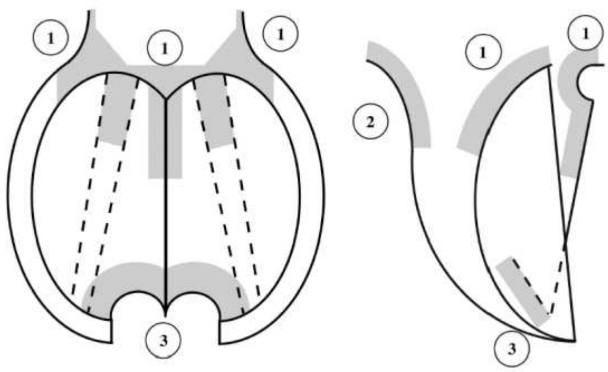


Fig. 1: *comparison of wear state of the two types of coating tested (left: standard wear right: HVOF)*

The EDF General Technical Division (DTG) has proposed studying the feasibility of NDT by active thermography. To do this, EDF DTG, in agreement with the Alps Production Unit of EDF, has developed a test programme to evaluate the feasibility of cracks detection under the HVOF coating using an Intercontrôle prototype, which concluded satisfactorily. Then the Photothermal Camera (PTC) was industrialized by Framatome-Intercontrôle during a collaborative project with other industrial partners. The expectation was to obtain an industrial PTC with improved capacities regarding inspection duration and portability and to bring it to the same level as standard NDT techniques. For this purpose, a technical justification approach was leaded in order to establish the NDT capabilities of the system in on-sites conditions.



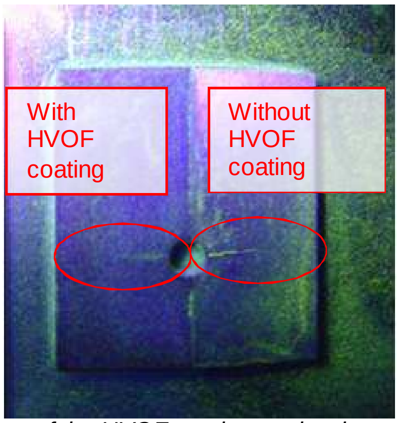


Fig. 2: *areas sensitive to cracking in Pelton buckets (left) - Effect of the presence of the HVOF coating on the detection sensitivity of the NDT by MPI (right)*

2. Thermography in Non-Destructive Testing (NDT)

2.1 <u>Introduction</u>

Thermography testing is a NDT technique based on the measurement of the temperature of the parts to be inspected. The analysis of the spatial and/or temporal evolution of the temperature provides information about the body's material, integrity or even geometry.

A very simple application of thermography is measuring the temperature of electrical connections: due to the Joule effect, a loose connection will produce more heat than a well-fit one, and it will be easy to differentiate them. Identically a shaft bearing with improper lubrication will heat up more than it should when rotating; this will indicate improper operating conditions. Here, the parts under inspection generate the temperature elevation during standard operation. The inspection system do not generates heat: this is called passive thermography. A major drawback of this family of techniques is that the inspection possibilities are limited to specific cases such as those listed above where the anomaly or the environment generate temperature variations.

Active thermography consists in generating the heat into the component, and is a more general technique. Two different approaches exists:

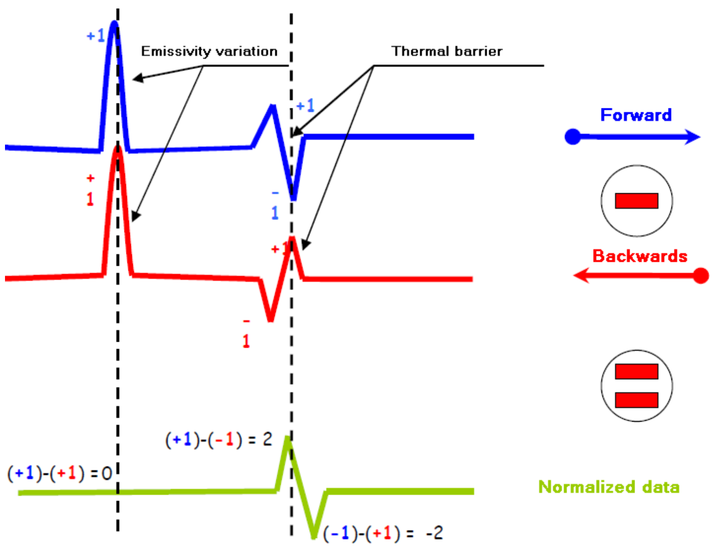
- techniques that induce global or local heat in the part bulk. The analysis of the heat diffusion within the part can provide an indication on the part's local heat conductivity. This conductivity can be affected by discontinuities, thickness variation, material non-homogeneity…. Typically hot or cold fluids (air, water…), light, laser, electrical conduction or induction heating are used for this purpose;
- techniques that generate heat directly at the location of a discontinuity thanks to the Joule effect or to mechanical effects such as friction. The defects will behave as heat sources, which the inspection system will detect. These methods can only detect discontinuities such as cracks, delaminations, lack of fusion…. Typically, vibration, electrical conduction or induction heating are used for this purpose.

The detection of heat patterns in inspected parts can be realized in different ways, some of which are contact-less. As explained by Planck's law, every body with a temperature above 0°K will emit infrared radiation. The infrared spectral density only will depend on the body temperature in the ideal case. An infrared camera can hence be used to obtain the accurate temperature of an object. Nowadays, infrared cameras have up to 1024x1024 pixels and reach a thermal resolution in the 0.01°K range. This means that a rise of only a few degrees of the inspected surface is enough to allow detection of the thermal flux perturbations over a wide area with high spatial resolution. This allows applying active thermography solutions for NDT applications.

2.2 The Photothermal Camera (PTC)

As explained above, if we want to inspect a part that does not produce heat by itself, the inspection system must induce heat into the inspected part. A very convenient way of doing so uses light: there is no need of contact with the part, and the power delivered does not vary with the distance if afocal lighting is used. A properly shaped laser fulfils this condition with high light power density and is the basis of the Photothermal Camera prototype. An infrared camera records simultaneously the evolution of the heat generated in the part using this laser light. As explained above, this allows the detection of different features of the inspected part.

The emissivity of the part inspected should not affect the thermography inspection. However, emissivity varies significantly according to different factors. One way to correct for its influence is scanning the part inspected two times: forward and backward. The impact of emissivity on the acquired images will be the same for both the forward and the backward images; however, the signal due to the disturbances in heat propagation will be reversed. A subtraction of the forward and the backward images will cancel out the emissivity signal, leaving only the image information due to the perturbation of the heat flux. Analysis of data acquired this way is straightforward.



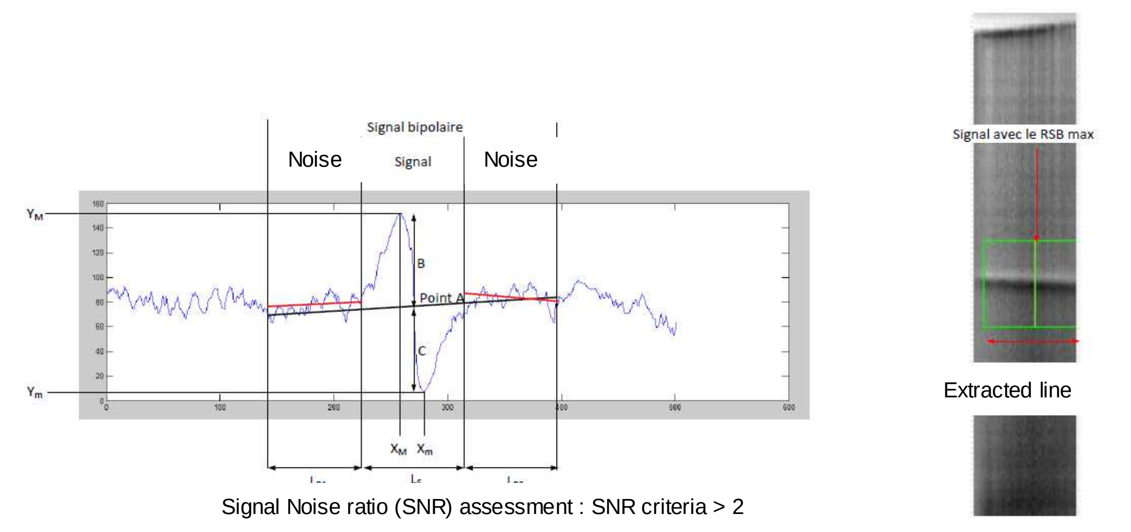


Fig. 3: *photothermal camera normalization principle – bipolar signal features*

One of the improvements of the new developed PTC concerns the improvement of the laser beam geometry. A new beam generation system, using new types of optical lenses permits to project a more regular laser beam. The figure 4 below show the comparison between the previous and new PTC laser beam. The new PTC system was also improved in terms of weight (reduced by a factor 3), dimensions (reduced by a factor 3), and ergonomy (only one software for the calibration, acquisition and processing). The figure 5 below show the new PTC during the inspection of a mockup with.an electro-eroded defect beneath the 300 micrometer HVOF coating.

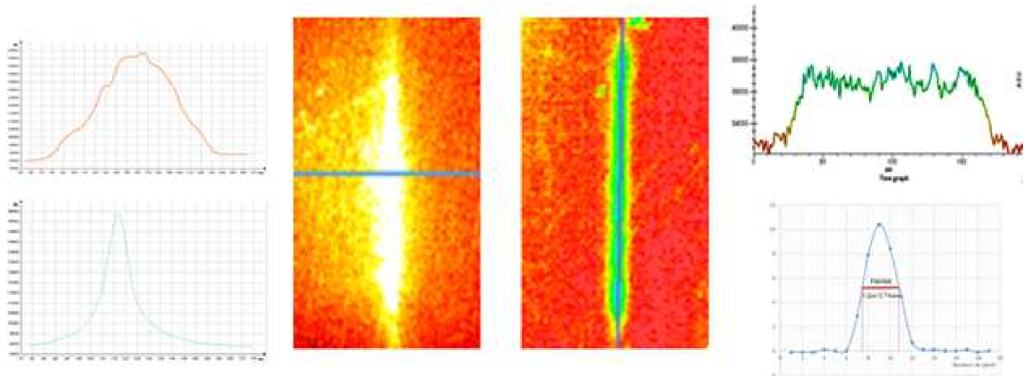


Fig.4: *longitudinal and transversal profiles of the 2 beams (prototype and new PTC).*

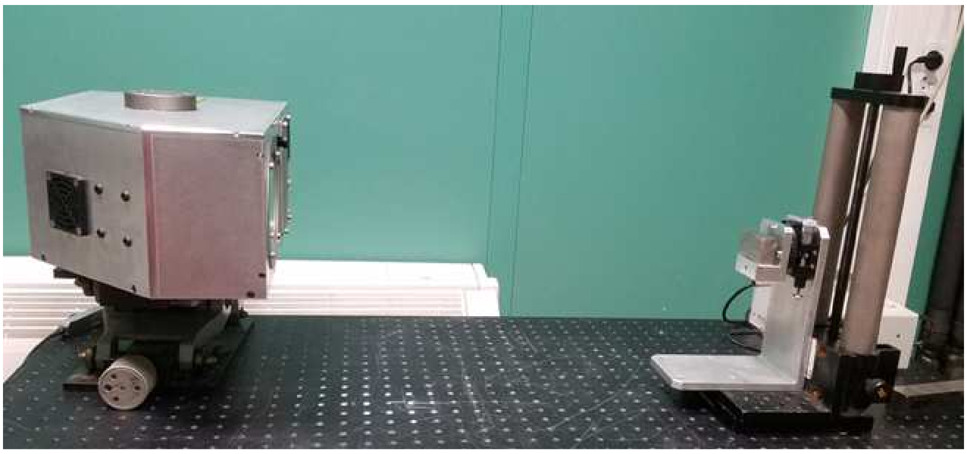


Fig.5: *test bench (CPA box and PP/AP06 mockup on a gripper)*

Thermography vs. MPI

The comparison of thermographic inspection using the PTC prototype and magnetic particle testing can be realized using the calibration samples from the existing EDF procedure. This calibration sample is designed according to EN 9934-2. It includes surface breaking fatigue cracks, as can be seen on Fig.6.

Using laser thermography, we can see that the crack networks can be detected the same way they are with magnetic particle testing. This concurs with the experience of Framatome-Intercontrôle has with this technique, which shows that its sensitivity is in the same range as MT for both surface breaking and underlying cracks on steel components.

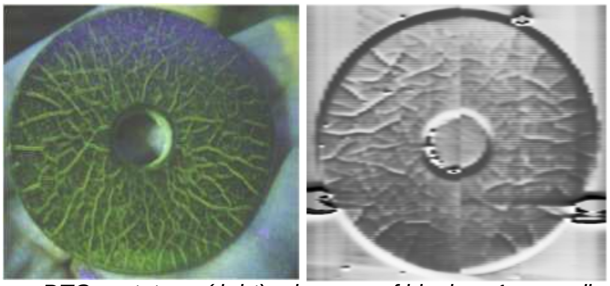


Fig.6: *comparison of MPI (left) vs. PTC prototype (right) – images of block nr 1 according EN ISO 9934-2 MPI standard*

3. LASER thermography of HVOF-coated Pelton wheels – NDT Qualification approach

This development followed a progressive approach defined by EDF according the CEN/TR 14748 standard which defines the need of qualification for new NDT systems when no existing standard can apply specifically. This approach help to determine:

- the appropriate PTC settings parameters which match the NDT requirement of the application;
- the impact of the influential/essential parameters in order to ensure to deploy a robust NDT solution in the industrial field of the application.

The influential/essential parameters can be classified in several following groups and need to be analysed regarding their impact on the capability of the PTC e.g on the sensitivity, sizing and coverture area:

- component,
- defects,
- environment,
- PTC parameters,
- procedure parameters.

This approach of Technical Justification (TJ) can be compared with the Recommended Practice (RP) of the European network for Inspection Qualification (ENIQ). The technical justification is the collection of all the information which provides evidence about the capability of an NDT technique as applied to a specific component.

All influential parameters whose change in value actually affects the outcome of the inspection in such a way that it can no longer meet its NDT capability will be considered as essential parameters and have to be checked from the operator before the PTC examination.

3.1. Modelling – setting PTC parameters

A first step was designed and realised with the support of Université de Bourgogne regarding the modelling of the full PTC system. The use of Comsol Multiphysics® - after a validation step with experimental results – allowed the definition of a first set of influential parameters of the PTC: power, scanning speed, distance of the PTC to the object, offset between the laser and infrared lines, orientation of the defect, distance from the top of the defect from the surface (remaining wall thickness).

3.2. Practical assessment - setting PTC parameters

For each NDT application, the settings parameters of the PTC have to be selected carefully taking account of the specific conditions of the NDT purpose.

Example of Influential Parameters (IP) of the PTC equipment which were explored during extensive tests made as well for the Direction Industrielle of EDF are given below:

- Spatial resolution (mm),

- Integration time (µs),
- Laser line length (mm),
- Laser Power (W), see figure 7,
- Laser Energy distribution,
- optical focal length (mm),
- Distance of the laser to the surface object (mm),
- Scanning speed (mm/s), see figure 7,
- Repeatability…

All the tests were made in laboratory conditions on mock-up containing surface breaking reference flaws (length 5 mm, depth 2 mm), and with mock-ups representative of the HVOF coating.

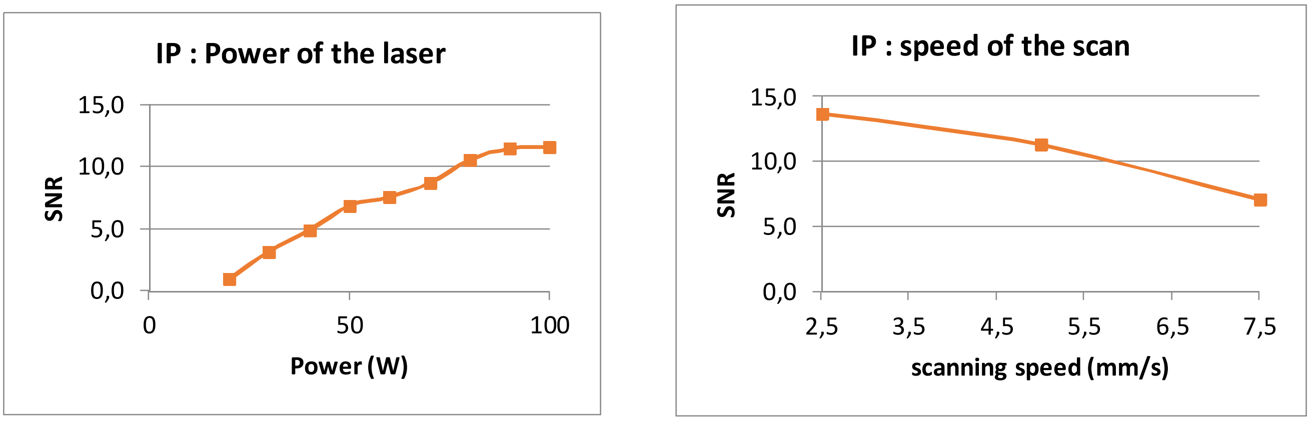


Fig. 7: *influential parameter – power of the laser – Signal to Noise Ratio on the references flaw in a nickel alloy plate.*

The first study allowed to select the nominal values of the settings PTC parameters. This helped to define the examination conditions for the PTC to obtain the best balance between:

- the Signal to Nose Ratio (SNR) which is determinant for the quantitative detection of the reference flaw (e.g. fatigue crack of 7 mm length, 2 mm depth under 350 µm coating thickness);
- the inspection duration of the 18 buckets of the turbine Pelton which shall not exceed 4 hours. The nominal scan speed of 5 mm/s was selected after this preliminary study.

3.3. Practical assessment - Technical Justification of the NDT capability

The second step of this study was lead to establish the NDT capability of the PTC regarding the realistic condition examination of the coated buckets of a Pelton turbine.

Following influential/essential parameters were analysed in their respective acceptable variation range regarding the application:

- thickness of the HVOF coating (variation range from 200 to 1000 µm : a set of 8 small mock-ups was especially manufactured for this purpose, each mock-up made of CrNi17-4 martensitic stainless steel contain a reference defect under the surface of the coating, see figure 8,
- angular disorientation of the PTC axis vs normal surface/ defect orientation : the variation range of the three space angles (along X,Y and Z axis) was defined with the help of a 3D CAD model of a Pelton turbine bucket and the test was lead on a mock-up to define the acceptable variation range of these essential parameters, see figure 9,
- sharpness: a typical exploration with a step of 10 mm in a range of 80 mm from each side of the focus point was lead in order to define the impact of the variation of distance between the examined surface and the PTC. This is an essential parameter in the case of the examination of a complex surface like the bucket of a Pelton turbine,

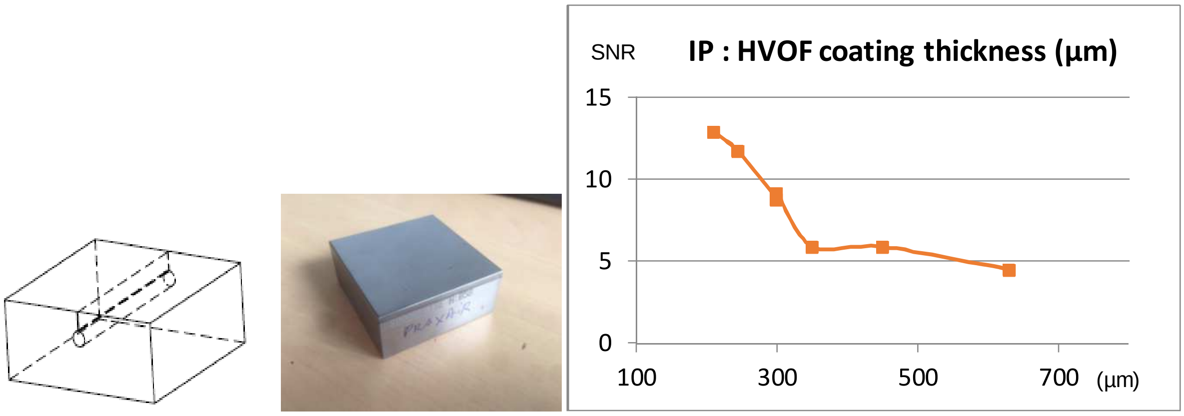


Fig. 8: *influential parameter – HVOF Coating Thickness – SNR assessment on reference defect*

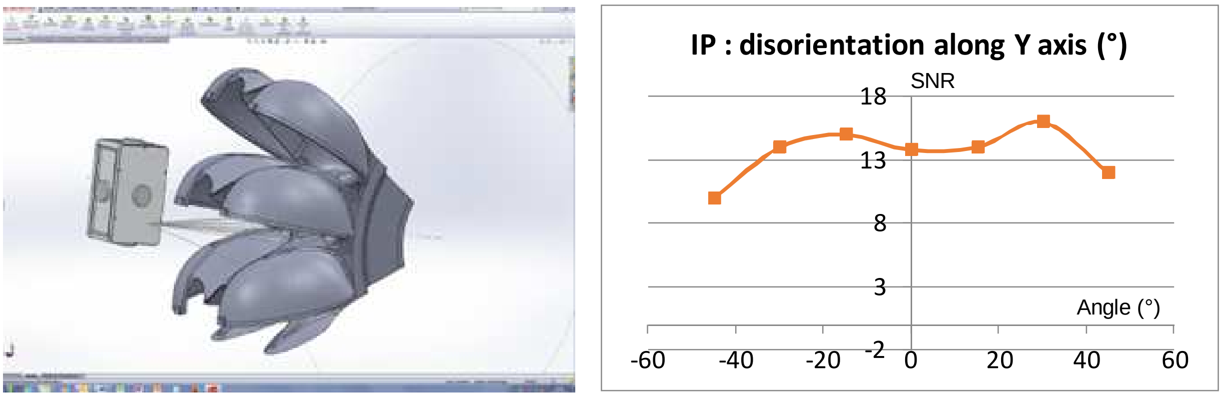


Fig. 9: *influential parameter – HVOF Coating Thickness – SNR assessment on reference defect*

As a result of the technical justification study, the first three parameters can be classified as essentials regarding the implementation of the PTC for the examination of HVOF coated bucket since:

- their respective acceptable range was properly defined: e.g. +/- 45° for a Y – disorientation, 200 to 600 µm max. coating thickness, +/- 60 mm defocalisation in order to guarantee the detection of the reference defect with an acceptable SNR (> 2) as defined in the trials and according the procedure;
- these parameters have to be checked from the operator since they may vary outside of their acceptable range according the real Pelton turbine bucket features to be inspected.

Regarding the last influent parameter, the trials confirmed that there were no significant impact expected on the detection capability whatever the position of reference defect relating to the PTC line axis. This parameter is not classified as essential. As consequence no overlapping was necessary during the examination in order to guarantee a sufficient coverage of the surface of the bucket.

Finally, a last trial was organised at an EDF –facility with a real Pelton turbine in order to check the usability of the future inspection procedure.

One bucket of this turbine contained a real fatigue crack under a 350 µm thick HVOF coating. The PTC was placed in front of the wheel as can be seen on Figure 10, and both areas were inspected in blind-test conditions from this position at a 750 mm distance. The results obtained and shown on Figure 10 clearly indicate an indication which matches the established criteria for the crack classification (see figure 3):

- signal to Noise ratio > 2;
- bipolar signal (positive/negative according the scan direction);
- peak-to-peak distance;
- length of the indication > 3 mm.

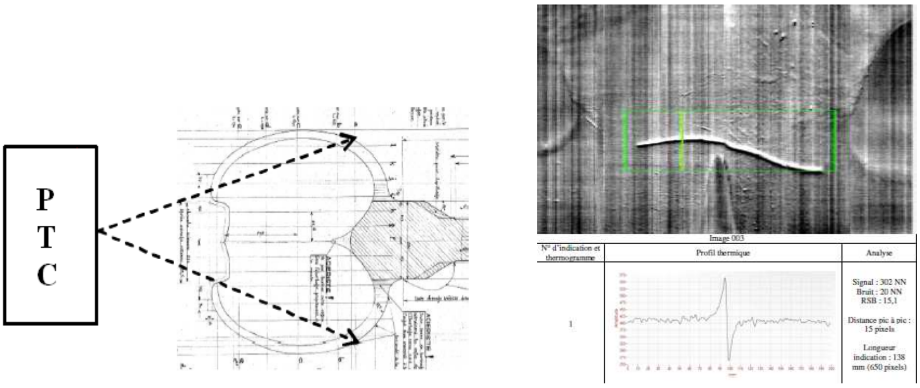


Fig. 10: *test of the PTC procedure on a real component including a real fatigue crack to be recorded*

Further trials were made in order to check the absence of impact of a disorientation of the PTC regarding the surface/defect and confirmed the results establish on elementary mock-ups in laboratory. A sufficient SNR ratio of the under surface crack was obtained along his profile whatever the lateral angular position of the PTC.

3.4. **First implementation of the PTC in realistic on site conditions**

Subsequently, the inspection system was brought into a realistic environment to perform an inspection of two HVOF coated Pelton turbine at a hydro power station in the French Alps. This allowed the evaluation of the potential environmental interactions during an inspection in a real hydropower plant, and provided data about realistic implementation of this inspection in terms of positioning, control rate and safety. The positioning of the camera for inspecting the areas described on Fig. 2***:*** requires a wide working range because of the various geometries that are at stake.

Fig. 11: *the PTC system under laser protection tarp during Pelton onsite inspection - Periodical check of the system before inspection with ATHENA software interface*

A specific carrier of the PTC – see figure 12 - has been developed and shows following benefices:

- repeatable positioning of the PTC for all bucket examination, that guarantees mastered conditions of examination for each bucket inspected – e.g. distance and orientation of the PTC axis ;
- minimization of the manual rotation of the turbine to inspect all the 18 buckets.

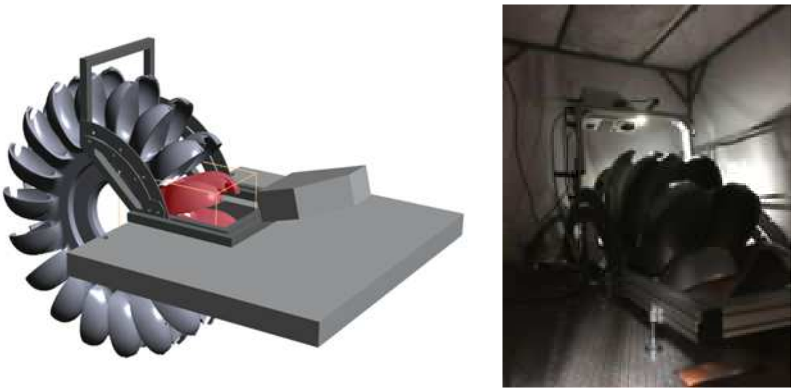
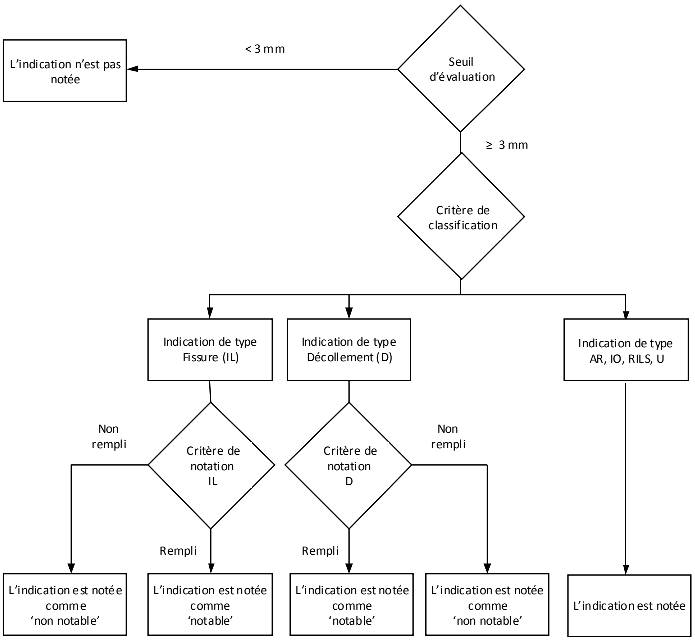


Fig. 12: *PTC with dedicated carrier for the on-site inspection*

The PTC inspection allowed to give the status regarding the fitness of service for these two wheels after the allowed inspection duration time. All inspected areas of the bucket were inspected and recorded accordingly the procedure. A specific chart flow diagram – see below - was developed in the inspection procedure as a support for the operators regarding the evaluation, classification and registration of the indications from the PTC software.



4. Conclusion

Framatome-Intercontrôle has developed – through a collaborative project - an inspection tool based on LASER active thermography, which does not have the limitations of current MPI (Magnetic Particle Inspection) for this particular NDT application. This new industrialised tool, called the Photothermal Camera, allows contactless inspection of complex surfaces in steel components for different types of defects, such as surface-breaking or sub-surface fatigue cracks.

Preliminary tests conducted at the Framatome-Intercontrôle and EDF facilities using the Photothermal camera allowed the detection of all defects defined by EDF into mock-ups as well in real components including surface breaking and under coating flaws, parallel or perpendicular to the surface.

The successful realization of this inspection in a real environment proved the possibility of a routine use of thermography for preventive maintenance of HVOF-coated Pelton wheels. Furthermore, a Technical Justification approach which consist in an experimental studies of the influential/essentials parameters shows that it was possible to establish the NDT capabilities and to qualify this new NDT solution according highest standards such as European ENIQ and French R-SEM qualification. The industrial PTC showed, as expected, improved capacities regarding inspection duration and portability. It was possible - with an appropriate technical justification approach - to bring it to the same acceptance level as standard NDT techniques.