Evaluation of the material's damage in gas turbine rotors by instrumented spherical indentation

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ABSTRACT. Experimental indentations are carried out on items of two different materials, taken in several location of various components from high pressure gas turbine rotor which have seen an extensive service. The components object of investigation consisted in 1st and 2nd high pressure turbine wheels made in nickel-base superalloy (Inconel 718), the spacer ring (Inconel 718) and the compressor shaft made in CrMoV low alloy steel (ASTM A471 type10).
Aim of the work is to set up the capability of the instrumented spherical indentation testing system to evaluate variations in the material properties due to damage, resulting from temperature field and stresses acting on components during service. To perform this task load-indentation depth curves will be acquired in various zones of the above mentioned components. The analysis of the results has allowed to identify an energy parameter which shows a linear evolution with the mean temperature acting on the components.

KEYWORDS. Instrumented indentation; Depth-sensing indentation; Material characterization.

INTRODUCTION

Heavy-duty and aircraft-derivative gas turbines rotors for power generation and industrial applications are among the most critical and highly stressed components of the plants and they are expected to reliably operate for a period which may be in excess of thirty years. Over the turbine's life the structural integrity of rotor materials naturally declines when subjected to the harsh conditions of gas turbine operation; high temperatures exposure, mechanical stress and startup/shutdown cycles result in the initiation and growth of flaws, which can eventually compromise the machine's safety and integrity.
Remaining life assessment methodologies employ a combination of traditional and high-tech non-destructive tools and methods to evaluate the mechanical integrity of rotors; therefore, they can be used to confirm the safety of continued operation or to recommend necessary restoration [1-4].
The measure of material's mechanical properties are a fundamental task in safety design and lifetime assessment of industrial components and among the in-field inspection and real-time monitoring non-destructive methods indentation-

based technique for materials characterization are a promising and attractive tool nowadays available in materials engineering and science [5-9].

Instrumented indentation holds several advantages: they are inexpensive, non destructive and it does not require specimen preparation; therefore, it may be used to investigate the material properties on small volumes, such as thin films, and soft tissues on small scales by just one simple impression test.

Indentation tests can be used to probe hardness of materials, toughness, elastic modulus, elasto-plastic behaviour and constitutive laws evaluation by different reverse analysis methods of indentation load-displacement curve [10-16].

Aim of the work is to set up the capability of the instrumented spherical indentation testing system to evaluate variations in a gas turbine rotor material properties due to damage resulting from temperature field and stresses acting on components during long time service.

To perform this task load-indentation depth curves were acquired in several location of various components made in IN718 and CrMoV from high pressure gas turbine rotor. Conventional hardness measurements were also carried out, in order to verify if a correlation can be obtained between these tests and indentations. Finally, whole results will be analysed to assess the material damage.

MATERIALS AND METHODS

Indentation testing apparatus

Experimental indentations were carried out using an instrumented indentation testing equipment developed by University of Pisa, University of Trento and Scienza Machinale S.r.l, able to performs a maximum indentation load of 2000 N - with a resolution of the order of 0.2 N - during the experimental tests. With this device it is possible to investigate the behaviour of the hardest metallic materials. Indentations were performed via a spherical tungsten-carbide ball having a diameter of 2.5 mm. The relative displacement between indenter and target was continuously measured by two LVDT transducers ensuring an accuracy of 4 μm and a resolution of 0.2 μm. Tests were carried out in displacement control at a speed of 1μm/s, thus ensuring that the data were collected under quasi static condition and no potential strain-rate effects were involved. The technical specifications of the testing machine are summarized in Tab. 1.

A detailed description of the design solutions can be found in [17].

Load cell	Loading axis	Indenter
Maximum load 2000 N	Maximum linear excursion 2 mm	Tungsten-Carbide Ball
Maximum error 1.5 N	Accuracy 4 μm	Diameter 2.5 mm
	Resolution 0.2 μm	

Table 1: Technical specification of instrumented indentation apparatus ("Diaptometro").

Test procedure overview

Indentations were performed on items sampling on 1st and 2nd stage turbine discs and on the spacer ring made in nickel-base superalloy (Inconel 718) from an high pressure GE turbine rotor which have seen an extensive service (over 10^5 hours). Moreover some test were carried out on the compressor aft stub shaft made in CrMoV low alloy steel (ASTM A471 type10) belonging to the same machine.

The items were machined so as to be free from thermal or mechanical alteration due to working process and to obtain a tolerance parallelism between surfaces minor of 0.05 mm and a tolerance flatness lower than 0.02 mm. Also, in order to achieve the right surface finishing, the items were polished. For each tested item a set of about 40 instrumented indentations and 15 conventional HBW hardness measurements were performed in significant areas, subjected during service to different values of stress and temperature.

In order to asses a statistical dispersion of indentation response, before the aforementioned testing campaign a set of measures was carried out on forging ring pieces of ASTM A182F22. To perform this task the items were machined to obtain the same surface conditions and tolerances.

Load-indentation depth (P-δ) curves and conventional HBW hardness acquired in the various zones of test samples were analysed as described in the following.

DIRECT ANALYSIS

Parameters evaluated from load-indentation depth curves

Instrumented indentation is widely used to probe the elastic and plastic properties of engineering materials. The indentation test can only provide the characteristic load P vs. penetration depth δ curve, a sequence of measured values ($P_i^{exp}, \delta_i^{exp}$), and a reverse analysis is therefore required to estimate the mechanical properties of materials (Fig. 1).

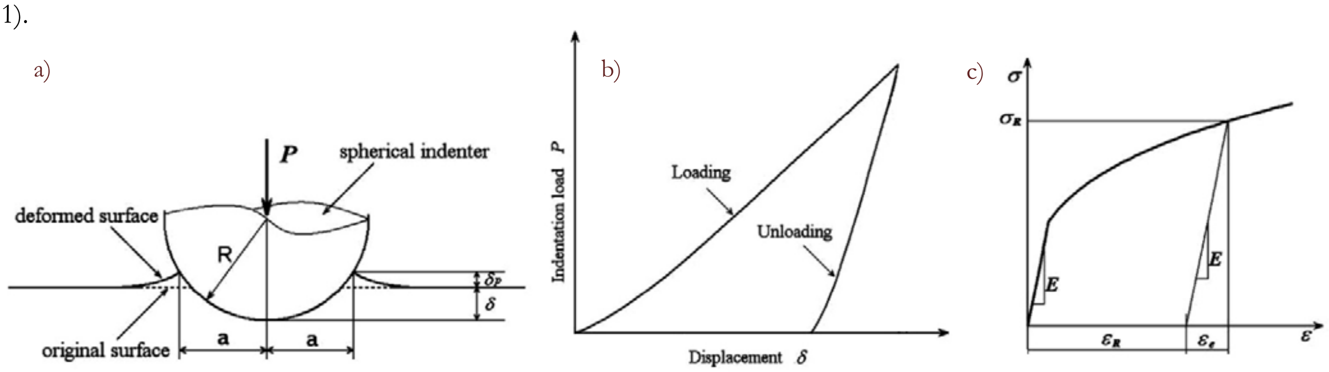

Figure 1: (a) Scheme of spherical indentation on a homogeneous, isotropic semi-infinite bulk specimen; (b) typical indentation load–depth curves obtained from an experiment; (c) the uniaxial stress–strain (σ–ε) curve of a power-law hardening solid.

Elastic modulus, E, has been widely employed to obtain damage evolution, using the fact that it shows a progressive degradation with damage. Therefore, by measuring the value of E it is possible to indirectly measure the value of damage according to the following common equation:

$$\text{DM} = 1 - \frac{E}{E_0}$$

where E is the effective modulus of damaged material and E_0 is the modulus of virgin material.
The stress–strain (σ-ε) curves of the materials are represented in Hollomon like power law form, identified by three parameters: the Young modulus, the stress of proportionality limit, σ_0, and the strain-hardening exponent, n. The σ-ε curve can be deduced from indentation test by means an optimization algorithm that minimize the function $\chi(E, n, \sigma_0, P_i^{exp}, \delta_i^{exp})$, which represents the global distance between the measured points and the theoretical curve defined by the material properties E, σ_0, n [18-20].
The reverse analysis of the indentation test involves three-axial stress state, as well as the highly nonlinearity of material behaviour, and the complexity of contact problem due to the presence of friction and size effect. Therefore it is the critical step of the whole procedure.
By evaluating E by means of indentation tests it is possible to estimate the damage. The promising potential of the idea is related to the possibility to correlate the damage parameter to stress and temperature fields, but the measurement of the elastic modulus obtained from σ-ε curves were not considered in this work enough accurate in consequence of a substantial data dispersion.
In order to set up the effective capability of the instrumented spherical indentation testing system to evaluate variations in the material properties due to damage resulting from long time service, the collected load-indentation depth curves were systematically analysed. In particular the parameters below listed were evaluated (Fig. 2):

- The maximum displacement, δ_{max}.
- The final depth, δ_f, i.e. the permanent depth of penetration after the indenter is fully unloaded.
- The elastic unloading contact stiffness, S (dP/dδ), defined as the slope of the portion of the curve during the initial stages of unloading.
- The value δ_i of the intercept on x-axes of the line with slope S starting from the maximum of the curve.
- The area included by loading and unloading curve corresponding to the total work done by the indenter, W.
- The value of diameter at the rim of the impression, d, evaluated in function of the value of penetration depth δ acquired by the LVDT transducers:

$$d = 2 \cdot \sqrt{\delta - (D - \delta)}$$

in which D indicates the indenter diameter.

- Some parameters calculated by the standard Brinnell formulation:

$$H = \frac{0.102 \cdot P_{max}}{A} = \frac{0.102 \cdot 2P_{max}}{\pi D \left(D - \sqrt{D^2 - d^2} \right)}$$

in which P_{max} indicates the maximum value of the applied force (N), D and d are expressed in mm.
Replacing d with the previous expression, the relationship obtained is:

$$H = \frac{0.102 \cdot 2P_{max}}{\pi D \left(D - \sqrt{D^2 - 4(\delta - (D - \delta)} \right)}$$

Using different values for the displacement δ three separate parameters H_1, H_2, H_3 were defined. In particular in H_1 the variable δ were set to δ_{max} value, in H_2 $\delta = \delta_f$, whereas in H_3 the value $\delta = \delta_i$ were used.

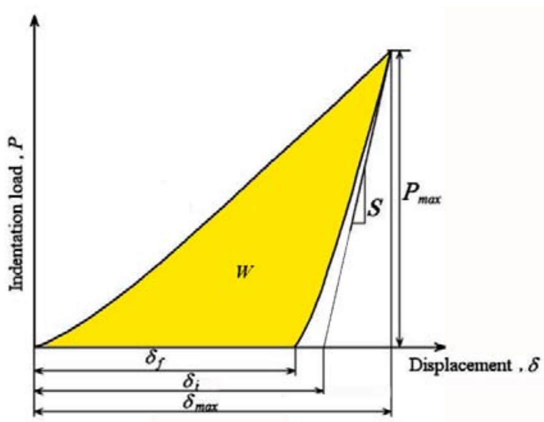

Figure 2: Parameters evaluated from load-indentation depth curves.

Note that because these definitions of "hardness" are not based on the contact area after unloading, they deviate from the traditional hardness measurement. Moreover, during the test the maximum value of the load is not maintained for a specific dwell time as the ASTM standard testing requires. So any evaluated hardness value cannot be in agreement with the standard, however the evaluated H parameters could be indicative of the material hardening. In all cases the penetration depth is calculated starting from the value of displacement at the first contact, assumed in correspondence of P = 1 N (Fig. 3).

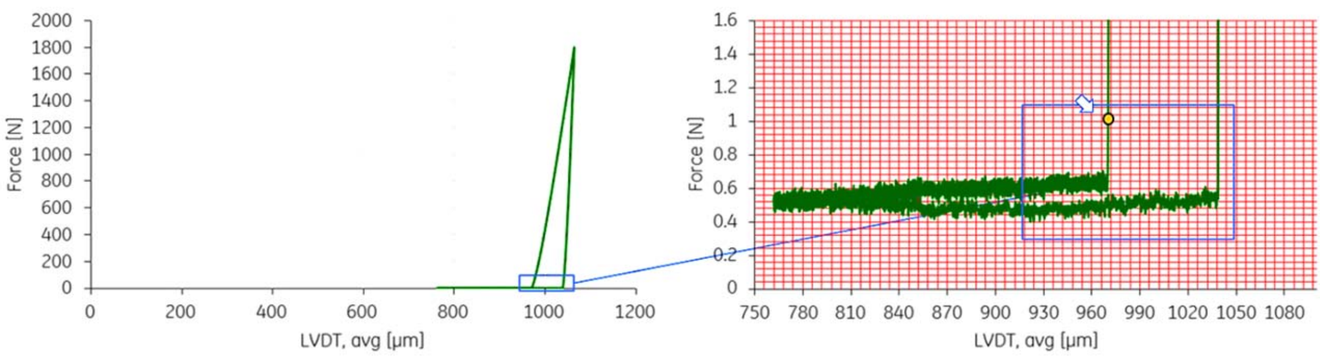

Figure 3: Estimation of penetration value δ at the first contact for P = 1 N used to calculate the parameters.

Experimental procedure

Initially, in order to asses a statistical dispersion of indentation response a set of measures was performed on a forging ring piece of ASTM A182F22 in "as is" conditions. A set of 25 indentation measurements were carried out using a maximum load of 1800 N and the maximum indenter penetration depth was measured. Tab. 2 and Fig. 4 respectively show an overview of the obtained values and the related Gaussian distribution, highlighting as the dispersion of indentation response is low.

Min	Max	Aver.	St.dev.
112.2	115.9	114.2	1.11

Table 2: Statistical parameters of the indentation response [μm] on a set of 25 measurements.

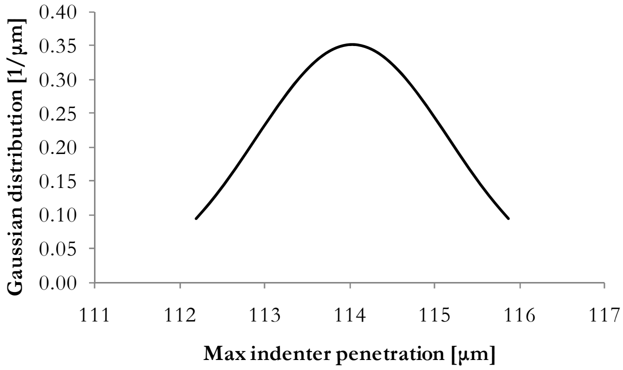

Figure 4: Gaussian curve of indentation response.

Aim of the research is to investigate the capability of the instrumented spherical indentation system to evaluate variations in the material properties, due to damage resulting from stresses and temperature fields during long time service. To perform this task, the sites of indentation were chosen considering both the thermal and the mechanical gradients on components, obtained from FEM analysis. For each component, the measurements were performed in order to analyse the whole surface. In particular, points positioned on lines parallel to the direction of the gradients were selected. Also conventional hardness measurements were carried out using the same criteria. Overall 130 spherical indentation and 50 conventional hardness measurements were performed in order to map the significant areas on the components.

Fig. 5a clarify the scheme of spherical indentation of the 1st stage turbine disc, underlining where sets of measure were carried out. Fig. 5b shows the dimensionless temperature profile obtained for an average engine running in ISO condition for, while fig. 5c shows the results of the 2D axial-symmetric elastic analysis at steady state condition.

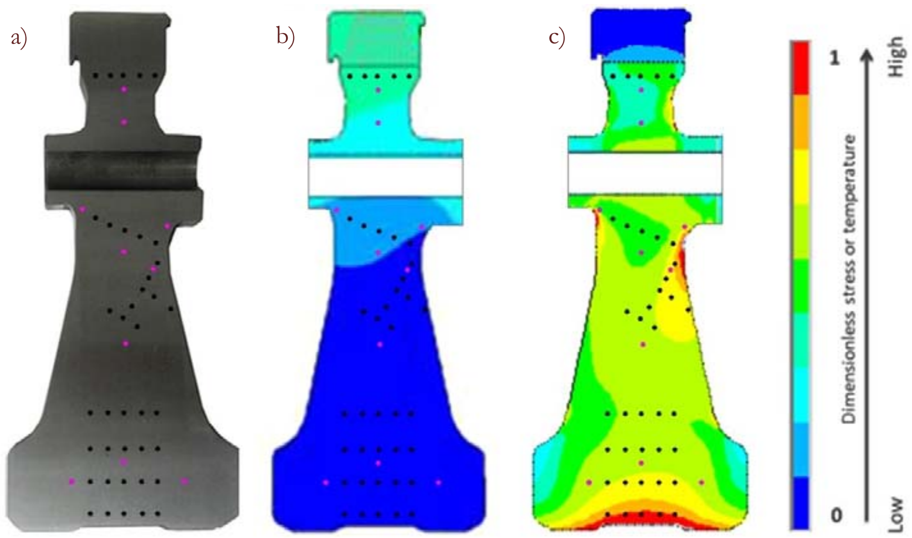

Figure 5: a) Positions of spherical indentation (red points) on item. In the yellow points are carried out conventional Brinnel tests b) Positions of spherical indentation (black points) overlying on thermal analysis c) Positions of spherical indentation overlying on structural analysis.

RESULT AND DISCUSSION

Data analysis

The comparison between the load-indentation depth curve obtained for ASTM A471 and IN718 was shown in fig. 6. The sensibility of instrumented indentation testing system to characterise different materials is highlighted. The analysis of the P–δ raw data is a good way to find promising indicators which might be useful to describe the behaviour of superalloy as well as alloy steel.

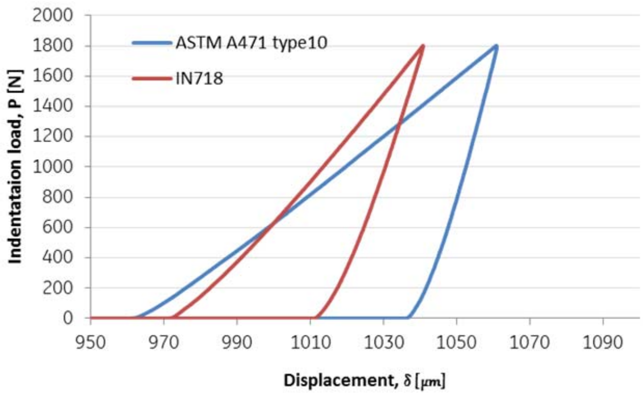

Figure 6: Comparison between the load-indentation depth curve for ASTM A471 and IN718 alloys.

An accurate analysis of all the previous detailed quantities obtainable from the load-indentation depth curves was performed for each items, to evaluate the possibility to correlate some parameters to damage.
Conventional hardness measurements were also carried out in order to find a relationship between these tests and indentations parameters. In fact, the hardness characteristic is correlate, to a certain extent, with the characteristics of many mechanical properties of a material, but the measured values was exhibit low sensitivity to structural transformations related to ageing in service, as observed also by the work of Lebedev [21].
The damage resulting in a serviced component is a function of time, stress and temperature. Turbine wheels and the spacer ring had seen the same extensive serviced time, about 10^5 hours, so it could not be a variable. Also the material was the same, so the variables of interest were the stress and the temperature fields.
As examples of the obtained results, in fig. 7 was reported for the rotor of the first stage the evolution of δ_{max}, δ_i and δ_f as function of stress, while the fig. 8 shows the variation with temperature of HB_1, HB_2 and HB_3.

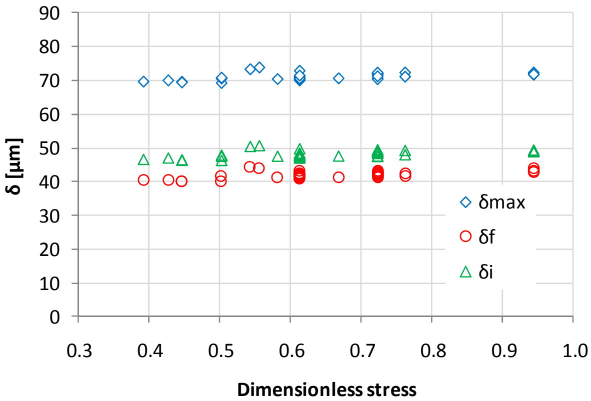

Figure 7: Evolution of penetration values δ in function of the stress field for the 1st stage wheel.

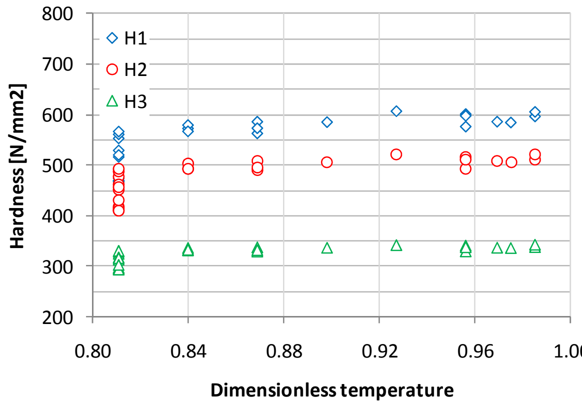

Figure 8: Evolution of hardness values in function of the temperature field for the spacer ring.

Since an indentation test is not very appropriate for detecting a mechanical damage, such voids or micro-cracks, firstly the stress was not considered in the analysis and the results were modelling as a function of the temperature.

Moreover, indentation sites at the same temperature performed on the spacer ring and on the 1st and 2nd stage of turbine wheels were considered equivalent points of measure. For each variable, the mean values among equivalent points were calculated and reported in function of the temperature. The analysis of all defined parameters had allowed to identify those which showed a monotonic and regular function. Among them, the most significant are the elastic unloading contact stiffness and the area included by loading and unloading curve (fig. 2).
A good fit solution was performed using a linear functions of mean data. Fig. 9 shows the obtained trend. The quantities S and W extrapolated from the P– δ curves could be used for a first assessment of the mean temperature of the component in the site of analysis, so these parameters are also promising indicators to material damage estimation due to extensive service.

a) b)

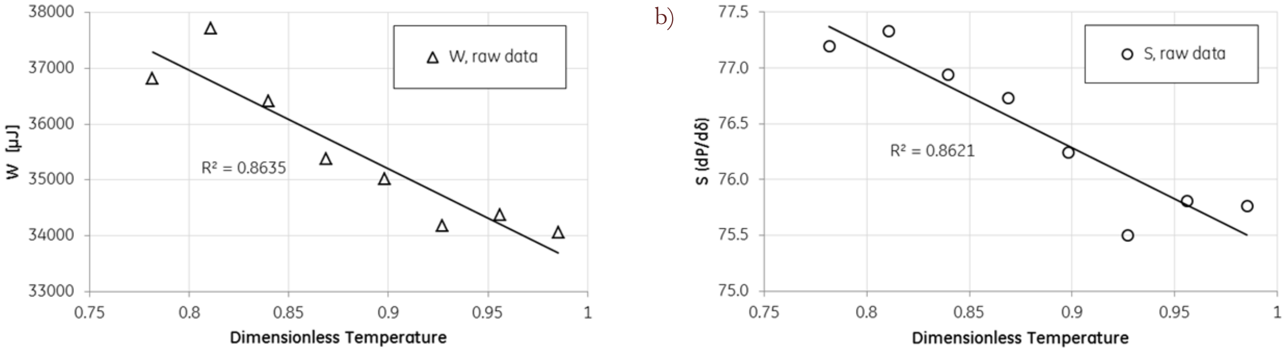

Figure 9: Total work done by the indenter a) and elastic unloading contact stiffness b) as function of mean temperature in indentation zone for serviced material (IN718).

Following this analysis, various objective function f(temperature, stress) were tested in order to include the stress field effect on damage. The stress acting on components was not considered as important as the temperature; its effect was therefore introduced as an amplification factor of the temperature values. In particular the functions shown in fig. 10a. Evolutions of the various parameters vs. the modified temperature were carried out and the accuracy of the fits was determined by the correlation coefficient R^2.
All the factors performed an improvement of the correlation coefficient, but the better result were obtained using the amplification factor $\frac{\sigma}{\sigma max}$ as shown in fig. 10b for the S parameter.

a) b)

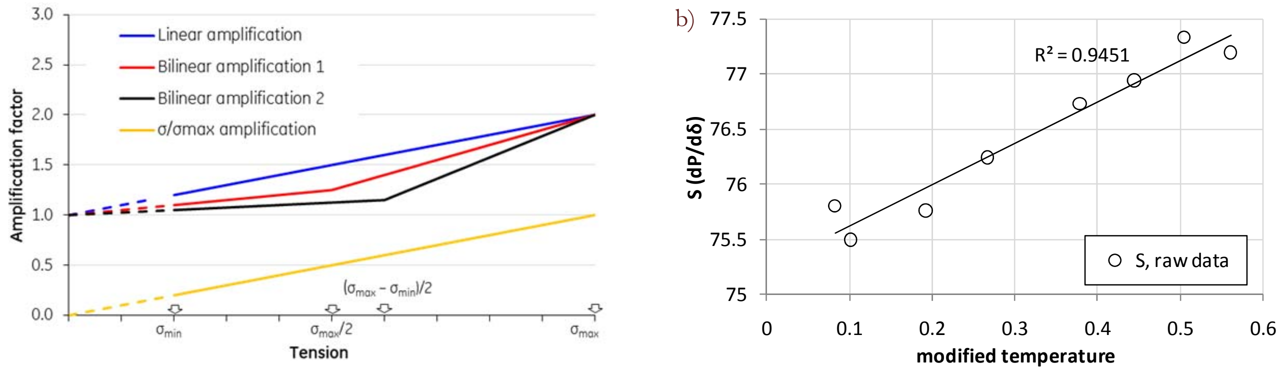

Figure 10: a) Comparison between three amplification factors proposed to include stresses effect; b) The relation between the elastic unloading stiffness and the modified temperature in indentation zone for IN718 in serviced condition.

CONCLUSION

An accurate analysis of several quantities evaluated from the load-indentation depth curve were performed on items sampling on turbine component in Inconel 718, with the aim to assess the capability of spherical indentation testing system to evaluate variations in the material properties due to damage resulting from service.

Indentation sites at the same temperature performed on the rotor components were considered equivalent points of measure and the resulting average values were reported in function of temperature. The most significant parameters related to temperature damaging are the elastic unloading contact stiffness and the area included by loading and unloading curve. These variables showed a linear behaviour with the temperature; after a calibration step, indentation tests may be used as an index of the average temperature acting on the component. So, these parameters are also promising indicators to material damage due to extensive service. The stress acting on components was considered an amplification factor of the temperature field. Using the linear factor σ/σ_{max} an improvement of the correlation was obtained.
The correlations proposed should be clearly verified with other tests. In fact, it is obviously that the performed study is still far from obtaining an analytical relation between a parameter, derived from the indentation test, and damage of the component; however, it demonstrates the feasibility of this task.

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