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EDF feedback shot-peening on feedwater plants working to 360°C - Prediction correlation and follow-up of thermal stresses relaxation

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ABSTRACT: Purpose of this study is to predict life duration of shoot-peening effect and finaly to allow the plant operator to prepare routine stopping. Four steps have been necessary to obtain this prediction : i) the shot-peening parameters must been choosen with care and implementation must be reliable and perfectly reproductible, ii) the residual stresses and cold working state cheeked by X-ray diffraction. This was done all over process, partly on samples, but mainly in situ on real components. A very precise method was followed in order to ensure the reproductibility of these NNDE's methods all over the usual periodic contol visits, iii) the EDF feedback on different steam-water system components working at around 300°C and repaired by shot-peening, like feedheater water boxes, water tanks and vessels, steam pipes, iv) a program, carried out on a feedwater tank repaired by welding and shot-peening and working at 360°C, on the correlation between expected and realities results is presented. To conclude one approach claimed to be economical and yet at the same time conservative is proposed.

1 SHOT-PEENING : PARAMETERS SELECTION

Shot-peening parameters selection is a delicate operation which will influence the effectiveness of shot-peening on mechanical parts subjected to fatigue, fatigue corrosion, thermal fatigue, stress corrosion, fretting, pitting and seizing.

	Residual stresses		Alteration on the roughness		Cold work	Surface elongation	Contamin ation	Defects damage
	Surface	Deep	Elimination of machining tracks or grooves	Fiction coefficient				
Fatigue	ΥΥ	ΥΥ	ΥΥ	|	Υ	|	|	ΥΥ
Thermal Fatigue	ΥΥ	ΥΥ	ΥΥ	|	|	|	|	ΥΥ
Media	ΥΥ	|	Υ		|	|	ΥΥ	Υ
Media diameter	Υ	Υ	ΥΥ		Υ	Υ	|	ΥΥ
Media Hardness	ΥΥ	ΥΥ	Υ		ΥΥ	Υ	|	ΥΥ
Kinetic energy of media	|	ΥΥ	ΥΥ		ΥΥ	Υ	|	ΥΥ
Incidence angle of media	ΥΥ	Υ	Υ		Υ	Υ	|	ΥΥ
Hammering (overlap, treatment duration)	|	Υ	ΥΥ		ΥΥ	ΥΥ	|	ΥΥ

table 1.

One of the most significant effects of shot-peening is residual compression stress introduction : this has a directly beneficial role against fatigue and thermal fatigue.
This residual stress is created by the combined effect of two separate phenomena (Guechichi 1986) : i) strain in the sub-layer induced by HERTZ stress, ii) extension of the skin at the surface. By varying the shot-peening parameters, in particular, kinetic energy, the nature, diameter and hardness of the bead, directly influences the distribution

ot residual stresses. The production of specimens and the measurement of residual stress can be rather involved operations, especially in the preliminary design stage. In this case, it can prove very advantageous to estimate the distribution of stress.

MécaSurf Laboratory perfected a program for calculating the distribution of residual stress induced by shot-peening involving several variables (Khabou 1989). For fatigue or thermal fatigue applications, as we can see on next table, the amount of residual stresses on the surface and in depth, the elimination of machining traces and a good accomodation between cold working state and the risk of defects damage are the major factors to choose parameters. So, in this case, we will use steel beads with hardness very close to hardness material and with diameter in relation to ALMEN intensity determinated before and in relation to geometry of the part (bead diameter increase with ALMEN intensity.

2 NON DESTRUCTIVE EVALUATION OF RESIDUAL STRESSES AND COLD WORKING STATE

The control on site of residual stresses had to be done in a reproductible way, on the same points so in a non destructive way. Even if different techniques are now on development such as ultra sonics or magnetic measurment, X-ray diffraction is the best candidate technique to full fill the requirements. It is widely used in laboratories, on small samples but also with portable equipments on large part. This techique is able to check local stresses, on surface from 1 to 10 mm² on surface layers (5 to 10 mm depth). In order to assure accuracy and reproductiblity, great cares have to be taken on experimental conditions and process. Experimental conditions used are the classical conditions of carbon steels (Cao 1989).

Two kinds of portable apparatus have been used all over study : STRAINFLEX from RIGAKU and the more recent SETX from ELPHYSE equiped with position sensitive detector. This last apparatus also uses a special software that takes into account the recent developments of the technique (Sprauel 1991). Before the measuements on site, a specific process is used : the justess of the apparatus is checked on a stress free powder and on stressed standard specimens. Results must be within the standard accuracy, with our conditions : +/- 25 MPa for 95 % confience.

3 EXAMPLES OF APPLICATIONS FOR EDF EQUIPMENT OPERATING BETWEEN 250 AND 360°C FEEDBACK (Gauchet)

3.1 *Feedback on low-pressure blades*

Shot peening was first used in EDF fossil power plants on the large low-pressure blades (exhaust side) of 600 and 700 MW units between 1978 and 1980. The foil and more particularly the fir-tree root for anchoring these 1100 mm (Z20CDV12-1 AFNOR : 0.2 % C - 12 % Cr and 1 % Mo steel) blades to the rotor are subject to fatigue phenomenon at 80°C-vibrations in the case of the foil, and fatigue fretting in the case of the root-which can result in loss of the blade with the risk of quite spectacular consequences.

Tests were carried out in the laboratory, using ALMEN test pieces, to determine the optimal shot-peening conditions, firstly on the leading edge of the blade, and then on the fir-tree root of eight most heavily loaded blades, installed in 1978 and 1980 into low-pressure cylinders of two units of different design and operating under different conditions (six 600 MW blades and two 700 MW blades).

After shot-peening, residual stress level are around -550 MPa for blades root and edge. There were no indication of crack reappearing. The residual stress from shot - peening remained at a satisfactory level (- 450 MPa) after 39,000 hours in service. These first results have been very encouraging. It is true, however, that they were obtained from equipment subjected only to mechanical fatigue. EDF therefore tried to use this process to remedy certain more advanced cases involving thermal fatigue phenomena on items of equipment such as feeder cells and supply tanks as well as the water chambers of heaters subject to heavy stresses as a result of heat and pressure transients.

3.2 *Feedback from feeder cells and supply tanks*

In certain very restricted zones, such as the seating edge of feeder cell seals (15MD4 AFNOR : 0.15% C and 1% Mn + Mo steel) on a 250 MW unit operating at 350°C, cracks appeared and were removed in 1977, then reappeared in 1982 and removed again. Two other identical design units in the 250 MW series of plants exhibited the same defects. At the time, owing to the initially satisfactory experience feedback from LP blades, this zone was shot peened . Twenty feeder cells in three units were treated in this way in 1982 and then monitored.

The rediscovery of cracks during the 1984 outage of the more sressed unit following after 10,057 operating hours and 205 start-up operations meant that a new campaign of shot peening was carried out on all units during the same year. These last experimental values should be used as basic value to estimate the time before repeening. For fossil plants a relationship linking operating hours (Hm) to the number of hot start-up operations (Nh), warm start-up operations (Nw) or cold start-up operations (Nc), can be used to evaluate the equipement ageing as equivalent hours (Hem): Hem = Hm + 5Nh + 50Nw + 150Nc . These equivalent hours calculated like that, should be compare with nuclear operating hours. In this case the criterion adopted to repeat shot peening on the feedwater tanks would be 37,000 equivalent hours.

3.3 *Feedback from HP heater water boxes (Gauchet 1993)*

The appearance of large thermal fatigue cracks in the water chambers of five HP heaters in two 250 MW units in 1984 remains a problem today. At this time, in the light of location of the affected zones (close to the tubesheet), the high service temperature (210 to 270 °C), and the frequent start-up and stopping of the two units, shot-peening was carried out and 4.000 hours and 69 start-up operation later, in 1987, reheater will be replace.

In 1990, eight heaters at a 600 MW unit, with combined total of 80.000 hours in service and 747 start-up operations, were affected. Cracks are around the joint radius between the water chamber and the tubesheet. Their depth ranged between 3 and 10 mm ; and were result of a thermal fatigue phenomenon. After the remaining of an available thickness was verified, immediate action was undertaken : cutting away, shot-peening and thermal stresses relaxation follow-up. The changes in residual stresses from shot-peening for the two 250 MW units (between 1984 and 1987) and the 600 MW unit (from 1990 onwards) are compared, which indicates a slight variability in performance (figure 1).

To date, no crack has reappeared on the eight 600 MW heaters. Feedback from 7.350 hours and 150 start-up operations, corresponding to 15.400 equivalent hours is extremely satisfactory. However, it should be noted that in the light of similarity of this equipment as much from the point of view of geometry and operation, EDF has studied the risk of cracking in the 252 HP heaters installed in French nuclear power plants in terms of the state of surface finish and the thickness margins in the fillet zone (Gauchet 1995).

4 PREDICTING THE DISTRIBUTION AND THE THERMAL RELAXATION OF RESIDUAL STRESS FROM SHOT-PEENING

After repair work consisting in metal deposition on the bases of the feedwater column, which had been severely affected by thermal fatigue, of a 250 MW tank (365°C, 15MDV4-05 steel) (Thoraval 1994) the bases were shot-peened and monitored specially in order to follow changes in residual stress.

However, the drum of a dismanteled 250 MW unit, with the same grade and aged under roughly the same service time, was an opportunity to provide wholly representative samples. It allowed to obtain: i) an extensive knowledge on metallurgical and mechanical properties of the material and on its ability to be strained, ii) to predict the distribution through the material of stress induced by shot-peening, iii) to optimise the shot-peening parameters, iv) and with a sound knowledge of stresses induced by the different loads in service, to predict thermal relaxation of residual stresses over time.

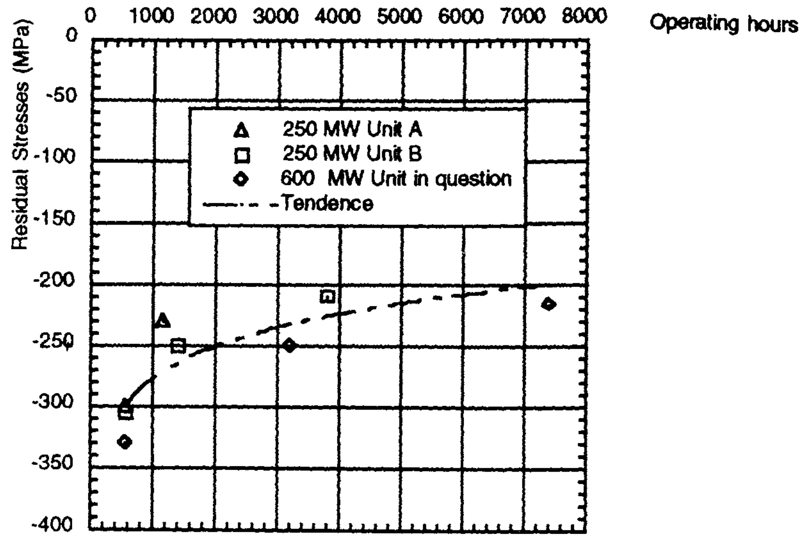

figure 1.

Hence, plates shot-peened under the same conditions as the tank bases were tested in the laboratory and their counterparts in the tank. Measurements of residual stress in the bases on a stress-free control zone of the tank, and each one of the plates taken from the device as it aged can be used to correlate the predicted state of the distribution of shot-peening stress and its thermal relaxation with the actual state.

5 MODELLING OF SHOT-PEENING

5.1 *Fundamental hypotheses*

The hypotheses adopted in the model are as follows (Cao & Fathallah 1989) : i) the beads are spherical and of constant diameter, ii) impacts are perpendicular to the surface with a constant velocity, iii) the material is uniform and isotopic ; its cyclic behaviour becomes stable under the effect of repeated impacts.

Law governing the behaviour of the material : the law of cyclic strain hardening is used to describe the behaviour of the material during shot-peening. A power function is used to express this law. Stress field induced by the impact : according to the theory of elastic contact, when a ball strikes a semi-infinite mass, it leaves a circular impression and induces a normal pressure on it. The stress applied is distributed as a function of the depth along the central axis and is given by the Hertz expression.

When instantaneous plastic strain is not induced by mechanical demand, and when the applied temperature remains below one third of the value of the melting point of the material, the effect of thermal restoration could be to blame a priori and could relax the residual stress induced by shot-peening. Recovery is mainly controlled by the mechanism governing the annihilation of the dislocations through interaction with voids in the cristal. This brings about a restructuring of the cristal and induces a permanent strain on the macroscopic scale. Thermal relaxation was postulated that the change in restoration strain is proportional in terms of stress to the microscopic strain observed in the ground level state (Cao & Khadhraoui 1994). Then, the associated residual stress can be calculated by an equilibrium calculation on the entire structure.

5.2 *Results*

Mechanical properties of 15MD4 grade steel were obtained with monotonic tensile and alternating tensile and compression tests. Specimens were taken along axis. Monotonic strain-hardening curve with the elastic limit, the breaking point, extension to rupture and the constants of power law were determinated. The cyclic curve to half-life was smoothed using an power function. Mechanical properties deduced are 211,600 MPA for Young's modelus and 0,3 for Poisson's coefficient.

The residual stress was calculated using the SHOTPEEN 2.2 program. The shot-peening conditions used correspond to the real conditions of shot-peening. The spray velocity was estimated at 26 m/s on the basis of results of measurements taken by the Wheellabrator laboratory (Fathallha 1994).

A comparison between the calculated and experimental residual stress modelled and that determined by X-ray diffraction provides us with the following information : i) good compatibility in the near surface zone (<0.2 mm), ii) 100 MPa out in the 0.2-0.5 mm zone, iii) good compatibility in the > 0.5 mm zone, iv) accurate projection of the depth affected.

Owing to our lack of knowledge concerning the porperties of this material at high temperatures, we are going to perform an explanatory calculation to forecast the thermal relaxation of residual stress induced by shot-peening. The calculation is carried out at 360°C for dwell times of 1, 10 and 1,000 hours (Gauchet & Reversat 1994). Successive values calculated in this way are shown in the following figure and compared by X-ray diffraction (figure 2).

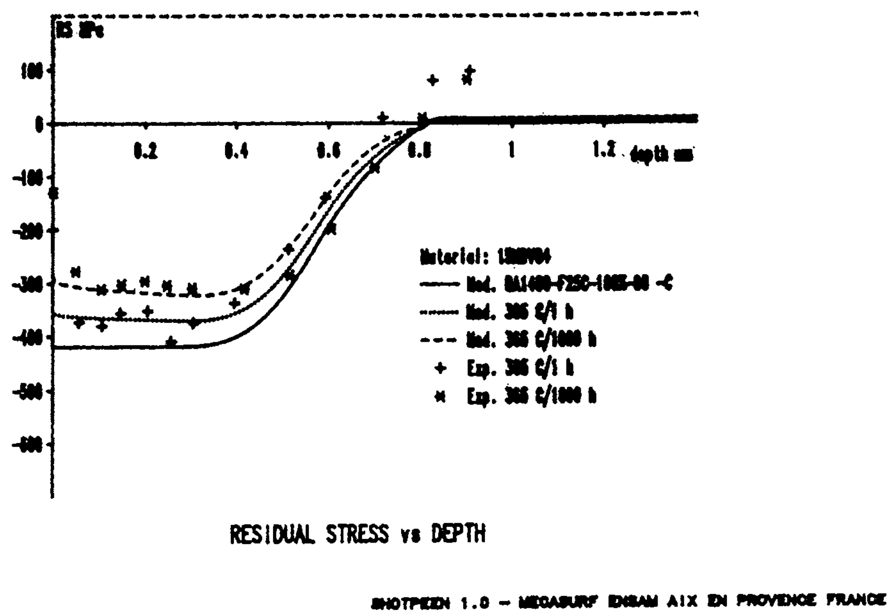

Figure 2.

A comparison with the theorical results shows that the theorical model indicates : i) greater relaxation at the surface than deep-down, ii) relaxation occuring during the first hour that the specimen is kept at temperature, nad then steadying out with time. The mechanical bias shot-peening model seems to correspond to experimental results obtaines by X-ray diffraction for the material in question. In situ, residual stress on the feedwater tank determinated at 100 μm depth can be compared with the predicted relaxation. A good correlation is observed figure 3.

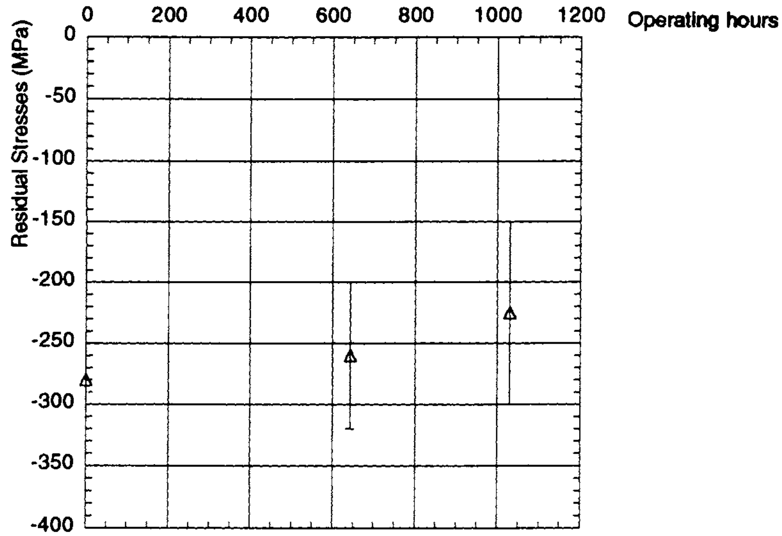

Figure 3.

6 CONCLUSIONS

For components subjected to thermal fatigue phenomenon, shot-peening can be used as a preventive process in order to extend life. Studies show that we can predict residual stresses induced by shot-peening and relaxation due to thermal transient effects.
A good knowledge of material caracteristics and structure mechanical and thermal loadings are necessary. Specific programs carried out on feedwater tank and reheater water boxes have shown a good correlation between prediction and experience. So, it's, now, possible to extend this approach to another components working in similar conditions, and estimate the time to regenerate compressive stress through repeening, before detecting any damage, and so, to be economical and conservative.

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