NDT Tools for Life Assessment of High Temperature Pressure Components

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Abstract. Creep damage of pressure equipment involves a great variety of high temperature components ranging from superheaters, reheaters, furnaces, reactors, etc.. Consequence of failures of these components are of high economic and safety concern. Moreover, the probability of failure of high temperature components is now increasing due to frequent cyclic of power plants imposed by a deregulated market and the search for increasing temperatures in ultrasupercritical plants. In this scenario, a complete NDT campaign is necessary both during the design stage and during the in-service stage. The choice of the specific NDT tecnique for each component type is of great importance. In this work an overview of the existing NDT techniques for creep designed and operated components are presented. Together with metallographic replica, which is still considered the fundamental tool for creep damage assessment in the majority of materials, other NDT tecniques which are able to detect creep cavity or cracks are presented and compared: ultrasonic techniques (tofd and phased-arrays), acoustic emission, holographic interferometry. In the second part of this paper the ability of some NDT tools to support residual life assessments are discussed. Among the most interesting tools are oxide scale ultrasonic measurement, micro-hardness testing, small-punch testing and on-stream deformation measurement. This tools are not strictly devoted to detecting creep defects (such as microcavities or microcracks) rather they give useful information related to creep damage, such as component deformation, material degradation and maximum service temperature. Moreover, a global procedure developed by ISPESL for inspection planning and interpretation of results of NDT examination according to a risk-based approach is presented. Eventually the new features of EN 13445-5 “Creep Amendments” concerning inspection and testing on creep designed components are briefly illustrated.

1. Introduction

High temperature components of pressure equipment in modern power plants are subject to increasing temperatures and cyclic loading. Moreover, economic concerns suggest to operate the plant close to design conditions. As a result the risk of creep, fatigue and corrosion damage of the most critical components increases more and more.
The increasing use of CEFS (“Creep Enhanced Ferritic Steels”) due to their ability to withstand high temperature loading may lead to serious problems during the welding process. Experience has shown several cases of high temperature cracking in high energy steam piping localized in HAZ.
As a result, the role of NDT in assessing component integrity of creep designed and operated components is becoming more and more relevant.
The aim of this work is to analyse the importance of NDT during the design stage and during the service stage of creep operated components.
NDT during fabrication focused on creep designed components are aimed at creating a “snapshot” of the “as-built” situation of the components at a starting *baseline*. For this purpose metallographic examinations together with dimensional measurements seem to be the most useful NDT techniques

NDT during service are a fundamental tool for residual life assessment as well.
Together with metallographic replica, which is still considered the fundamental tool for creep damage assessment in the majority of materials, other NDT tecniques which are able to detect creep cavity or cracks are presented and compared: ultrasonic techniques (tofd and phased-arrays), acoustic emission, holographic interferometry.
In the second part of this paper the ability of some NDT tools to support residual life assessments are discussed. Among the most interesting tools are oxide scale ultrasonic measurement, micro-hardness testing, small-punch testing and on-stream deformation measurement.
This tools are not strictly devoted to detecting creep defects (such as microcavities or microcracks) rather they give useful information related to creep damage, such as component deformation, material degradation and maximum service temperature.
ISPESL, namely the Italian Authority for Pressure Vessels and Boilers, has recently implemented a global procedure for the inspection campaign based on a risk-based approach. In this procedure NDT play a fundamental role, both during the preliminary stage (inspection planning) and during the final stage (determination of the inspection intervals).
Eventually the new features of EN 13445-5 “Creep Amendments” concerning inspection and testing on creep designed components are briefly illustrated in order to show the importance of NDT during the design stage.

2. NDT tools for creep damage detection

As known, incipient creep damage begins in the form of isolated micro-cavities. With time the micro-cavities increase in dimension and size and eventually degenerate into micro-cracks.
With no doubt metallographic replication is the most common tool for detecting cavities and cracks of microscopic amplitude.
Recently a great emphasis has been put on modern ultrasonic techniques such as TOFD or Phased Array which seem to have interesting features with respect to creep damage detection and characterization.
Some relevance seem to have Acoustic Emission techniques with the limitations on the minimum detectable damage.
A typical inspection program on creep operated components is divided into three steps:

1. Standard inspection devoted to detecting surface and volume defects (Visual Testing, Dye Penetrant, Ultrasonic and X-Rays techniques, etc.);
2. Extended inspection for detecting and characterizing creep micro-defects (metallographic replication, advanced ultrasonic techniques, acoustic emission, etc.);
3. Additional inspection with specific NDT tools for supporting residual life assessments (strain measurements, temperature assessment, etc.).

2.1. Metallographic replicas

The extensive use of metallographic replicas during the in-field inspections of creep operated components is justified by their effectiveness and simplicity to detect creep damage from the early stage of micro-cavities.
On the other hand for some steels (such as 9-12% Cr steels) local micro-structural changes in HAZ are brought about in a rather late phase of the lifetime. According to some authors [8] results of metallographic replicas are strongly related to the skill of the operator.
Onother limitation of the method is related to the ability to detect only surface or defects.

To keep the replica investigation *non-destructive* the total material removed by grinding must not exceed 0.5-1mm.

2.2. Ultrasonic Techniques

UT techniques are very helpful for detecting creep damage even if their *in-field* use is not so broad as for metallographic replicas.
Among them TOFD and Phased Array are the most interesting.
TOFD is able to detect defects down to the size of micro-cracks and, in certain corroborated cases, to relatively high density aligned cavitation. TOFD is utilized over the entirety of weld seam lengths for cost-effective and expedient detection.
UT methods based on Phased Arrays are highly effective due to the use of a number of array elements pulsed with the appropriate time phasing. Time delays applied to each transducer allows for longitudinal scanning, electronic focusing and beam steering.
These enhanced features of LPA (Linear Phased Arrays) allows for a faster inspection than TOFD.
Using focused beam inspection the phased array technology becomes even more effective: focus is accomplished using a special focusing lens to concentrate the available energy into a small focal spot. In the FATS technology small spot size and high beam intensity provide a superior sensitivity and resolution for detecting incipient creep damage.

However, like any other UT technique, FATS has a detection threshold so that the minimum detectable size cannot identify with a single cavity but with a given alignment.
A common inspection protocol utilizes a combination of time-of-flight diffraction (TOFD) and focused array transducer system (FATS).
In such a way it is possible to scan rapidly long portions of seam welds (TOFD) and investigate in deeper detail areas of greater interest wherever creep damage is suspected (FATS).

2.3 Acoustic Emission

Acoustic emission techniques are passive monitoring techniques able to detect “active” or growing defects. Moreover emission sources can be “source-located” by time-of-arrival techniques.
EPRI experience [5] has shown the importance of Acoustic Emission techniques for standard inspection of pressure equipment. A preliminary AE inspection can point out critical areas to inspect by specific NDT methods devoted to detecting creep damage.

As specified by some authors AE is able to detect small cavitation as well [12]. Anyway this feature of AE is not confirmed by practical experience. Other authors more realistically indicate that microvoid coalescence is not detectable by AE [13].

2.4 Holographic and Speckle Interferometry

The ESPI methodology (Electronic speckle pattern interferometry) [6] requires the use of a laser source and a video camera.

The main use of these methods is to detect defects and flaws just looking at the interference patterns. By comparing two images (reference signal and perturbed state) this method allows to detect deformations and displacement (allowing precise strain measurements up to 10^{-5}).

A useful application of this method is to monitor critical areas of components, by a combination of several NDT techniques. At the moment ESPI and Holography are seldom utilized for practical applications.

3. NDT tools for residual life assessments

3.1 Oxide scale measurements

In order to determine the residual life of SH/RH headers it is fundamental to estimate its average operating temperature. This value can be determined as a function of the thickness of the oxide scale in the inner side of the tube. In fact a higher steam temperature leads to a faster oxidation kinetic.
Measurement of both oxide thickness and base material thickness can be made simultaneously using a special UT technique.
Oxide Kinetics can be used as an effective fitness-for-service tool which can give useful information for the determination of re-inspection intervals.

3.2 Hardness measurements

Hardness test and replicas are commonly performed simultaneously in order to have additional information on the mechanical characteristics of the component.
Hardness normally varies with time, temperature and stress. In general hardness decreases with time whenever the component is operated at creep loads.
One of the possible applications of the hardness measurement is to estimate the real working temperature of the component. On the other hand creep resistance cannot be correlated with hardness measurements.
A possible correlation between hardness and Larson-Miller Parameter is the following [11]:

$$\frac{H}{H_0} = a * PLM + b * PLM^2 + c$$

where a, b and c are numerical coefficients.

A particular application of hardness measurement is micro-hardness. A special prototype was set up in 1956 for creep measurement. An interesting application of the method is for on-line hardness measurements [6].

3.3 Small-punch testing

The small punch testing can be considered as a non-destructive technique because of the limited amount of material to be sampled with the specimens being discs 0.25 – 0.5 mm thick and 8 – 10 mm diameter. No repair is usually necessary after the removal of the disc.
It is a efficient and cost effective technique which has the potential to measure the realistic material properties (such as material toughness or creep resistance) of the component under consideration.
This technique is undergoing a harmonisation procedure (CEN WS 21) in order to develop a european standard.

An important application of the method is to support residual life assessments. For this purpose this technique is included in the ISPESL Fitness-for-Service procedure for creep operated components.

3.4 Meaurement of creep deformation

Creep damage is always characterized by component deformation whose rate depends strongly by the creep stage (primary, secondary, tertiary).
Therefore, it is obvious that measurement of deformations during inspection campaigns, can give precious information on the level of creep damage.

- Continuous *on-line* monitoring is the most effective and can be carried out using capacitive strain sensors;
- Off-line monitoring is carried out at given time intervals using Image Correlation or Laser Profilometry.

Capacity strain sensors are commonly used for monitoring the strain in the base material.
Image correlation methods are more suitable for monitoring the heat –affected zone in a weld. The method developed by Kema (SPICA) involves making an optical fingerprint of a given surface in order to compare it with another image recorded at a following step. Local and integral strain can be calculated. Evaluation criteria are based on the results of tests conducted on test specimens; for HAZ the criteria are based on the elongation on this particular area.

Laser profilometry is used for measuring the inner profile of piping. With this technique accurate measurements of tube diameters are possible, allowing to detect incipient creep damage by measuring a 2% diameter increase.

3.5 Correlation between metallographic replicas and life fraction

A very important application of metallographic replicas is to correlate the result of the test with the actual residual life of the material.
The experimental correlation of Ellis [9] (partially revised by Sampietri [10]), shown in table 1, is valid only for some steels (1-1/4 Cr – ½ Mo, 1 Cr 0.5 Mo, 2.25 Cr- 1Mo) and is not applicable to weld metal.

Any other model (for example A-Parameter) based on the number of cavitated grain bounderies is scarcely reliable.

Table 1 – Correlation between Creep Damage and Life Fraction

Classificazione Welder-Neubauer	Life fraction (Ellis)	Life fraction (Sampietri)
-	0,27	0,181
A	0,46	0,442
B	0,65	0,691
C	0,84	0,889
D	1	1

Only by taking real pictures of metallographic structures it is possible to create a metallographic atlas which enables to show the material evolution with temperature and time.
In such a way it is possible to compare the actual material structure with the one given in the atlas in order to assess the component working temperature which may lead to more reliable residual life evaluations.

4. NDT effectiveness

Each of the previously described NDT technique is effective with respect to a particular level of creep damage. As shown in table 2 replica and focused array transducer system (FATS) seem to be very effective from the stage of incipient creep damage.

Table 2 – NDT effectiveness with respect to creep damage detection
(1: very effective, 2: moderately effective, 3: possibly effective, X: not normally used)
(*) only active defects, (**) only surface defects

	TOFD LPA	FATS	AE	ESPI	Replicas
Isolated micro-cavities	X	1-2	3*	X	1**
Aligned cavities	3	1	3*	X	1**
Micro-cracks	1-2	1	1*	1-3	1**
Macro-cracks	1	1	1*	1	1**

Table 3 shows the effectiveness of some NDT tools to support residual life assessments. These techniques are aimed at detecting physical variables (working temperature, mechanical properties, strains, etc.) which are directly related to the consumed life.

Table 3 – NDT effectiveness to support residual life assessments.
(1: very effective, 2: moderately effective, 3: possibly effective, X: not normally used)

	UT Oxide scale measurements	Hardness	Small Punch	ESPI - Laser Profilometry	Metallographic Replicas.	Estractive Replicas
Working temperature	1	1-2	X	X	X	1-3
Mechanical properties	X	1-2	1	X	X	1-2
Deformations	X	X	X	1	X	X
Life fraction	X	X	X	X	1	X

5. NDT on high energy piping

High energy piping are critical components with respect to creep and fatigue damage due to the very high working temperature (>500 °C).
UT techniques are very effective for inspecting this kind of components. A typical inspection strategy includes a TOFD (time-of-flight diffraction) scanning of the whole tube length followed by a specific FATS (focused array transducer system) investigation on critical areas.
UT techniques require removal of scaffolding and plant outage. On the contrary acoustic emission techniques can on-line monitor the plant and are very cost effective.
They only require the installation of wave guides welded to the tubes. Monitoring is normally conducted on-line during a whole week of operation.

6. NDT during fabrication of pressure equipment

Among the various standards that can be used to fulfill the essential safety requirements of PED Directive a major role is played by European Harmonized Standards. The most important standard harmonized with the PED Directive is EN13445 "Unfired Pressure Vessels". In the original version the norm did not include creep features. Recently the Task Group "Creep" of CEN TC54 has released a first draft of "Creep Amendments" which has undergone public enquiry and therefore it is now under revision.
The Italian delegation was appointed to prepare a proposal for EN13445 part 5 conecerning EN 13445-5 "Inspection and Testing".
The main aspects that were taken into account are the following:

- Definition of the testing groups;
- Extent of non-destructive testing;
- Additional NDT during fabrication.

6.1 Definition of the testing groups

For creep designed welded joints the Task Group "Creep" of CEN – on the basis of the comments received – has decided to accept both testing group 1 and 3 (Addressed as 1c and 3c). This applies only for welded joints working under creep load. For the remaining welded joints the usual groups apply.

6.2 Extent of non-destructive testing

As far as the extent of NDT is concerned the Working Group has proposed a general increase the percentages contained in EN13445 in order to guarantee a sufficient degree of confidence regarding the absence of defects which may grow under creep load.
The comments regarding this part should be furtherly discussed by the Working Group.

6.3 Additional NDT during fabrication

The new feature of the "creep amendments" of EN13445 is to take into account - to some extent - the future service life of the component. For instance, a smaller safety coefficient is permissible whenever a monitoring system for the operating conditions will be provided.
In order to have some information concerning the as-built metallurgical state of the welded joints of creep designed vessels it is advisable to perform - in addition to conventional NDT - metallographic replicas and hardness test. These information might be useful for assessing the structural evolution during service.

The norm also suggests to execute high precision diameter examinations of creep designed components (piping, etc.) in order to be able to detect any creep deformation at future inspections.
This part of the standard might be subject to modification after further discussion.
Dimensional measurement should guarantee the following degree of precision:

0.01 mm	up to 100 mm
0.02 mm	$100<D\leq500$ mm
0.05 mm	$500<D\leq1000$ mm
0.1 mm	from 1000 mm

7. Monitoring

Monitoring of operational parameters (temperature and pressure), is highly recommended for creep operated components.
Two different types of monitoring are possible:

- On-line monitoring of operational parameters (temperature, pressure) and mechanical parameters (typically strains);
- Off-line monitoring of operational parameters (temperature, pressure) and mechanical parameters (strains, hardness, creep damage, etc).

8. Risk-Based approach for defining re-inspection intervals

A risk-based procedure for defining re-inspection intervals was implemented by ISPESL.
In this procedure a fundamental role is played by NDT.
In order to determine which type of NDT technique to perform it is advisable to refer to the type of weld.
Weld types are classified according to their *criticality*. This parameter is strictly correlated with the consequences of a failure of a given welded joint: very low (A), low (B), medium (C), high (D). Criticality of base material is considered to be very high (E).
As an example table 4 shows a typical chart for the determination of the extent of NDT in a boiler header working in the creep range. As shown in the chart for each type of welded joint specific NDT are suggested whose extent increases as the PEC parameter increases. Additional NDT are suggested whenever a deeper investigation is required.
The procedure under consideration considers two different routes that can be followed to define inspection intervals on the basis of the result of NDT.
The first route (route A) applies to the case of creep damage only as long as no creep cracks are detected (uniform creep damage with cavitation).
The second route (route B) applies to the case of creep cracks (creep level 4 and 5).
Route A refers to a chart which correlates the Creep Damage Level with the criticality of the welded joint, giving as a result a Global Risk Level (PIR – table 5).
In case of damage levels IV and V corresponding to microcracks and macrocracks table 5 cannot be applied. In this cases the Fitness for Service procedure should be applied.
From the PIR level it is possible to enter table 6 which gives the inspection intervals as a function of the category of the inspection.
Using this procedure it is possible to increase the inspection interval by increasing the effectiveness of the inspection. This can be done – for example - by incresing the extent of NDT choosing a higher value of the PEC parameter.
Referring to the boiler header with a creep damage level 3 on a B type weld, the application of this method leads to a global risk level of 3 and a short re-inspection interval (around 10’000 hours). The interval can be increased (up to 15’000 hours) by increasing the inspection effectiveness from medium to very high.

The re-inspection interval can be extended in the following cases:

- a monitoring system is provided;
- additional tests during fabrication are conducted;
- the operating hours are relatively low;
- the creep rate is low as confirmed by replica examinations;
- strain measurements are carried out;
- additional NDT tools are carried out during service (Oxide scale measurement, hardness, etc).

Table 4 - Extent of NDT for a boiler header as a function of weld type

*

			Extent of NDT (PEC)				
Weld Type	**NDT**		**Limited PEC 1**	**Low PEC 2**	**Medium PEC 3**	**High PEC 4**	**Very High PEC 5**
A: header/non-pressure parts		**VT**	100%	100%	100%	100%	100%
		PT (or MT)	60%	70%	80%	90%	100%
	Additional	**ST**	*	*	*	*	*
B: header/small nozzles (De<100)		**VT**	100%	100%	100%	100%	100%
		ST	1% (max 2, min 1)	1,5% (max 2, min1)	2% (max 2, min 1)	3% (min 2)	5% (min 2)
		MT (or PT)	10%	20%	30%	40%	50%
	Additional	**ET**	*	*	*	*	*
B: header/big nozzles (De≥100)		**VT**	100%	100%	100%	100%	100%
		ST	1	1	1	2	2
		UT	70%	80%	90%	100%	100%
		MT (or PT)	70%	80%	90%	100%	100%
	Additional	**RT**	*	*	*	*	*
D: circumferential or shell/flat heads		**VT**	100%	100%	100%	100%	100%
		ST	1	1	2	2	2
		UT	80%	90%	100%	100%	100%
		MT (or PT)	70%	80%	90%	100%	100%
	Additional	**RT**	*	*	*	*	*
E: Base material		**VT**	100%	100%	100%	100%	100%
		UTS	**	**	**	**	**
	Additional	**DM**	*	*	*	*	*
Internal surfaces		**VTE**	20%	30%	50%	80%	100%

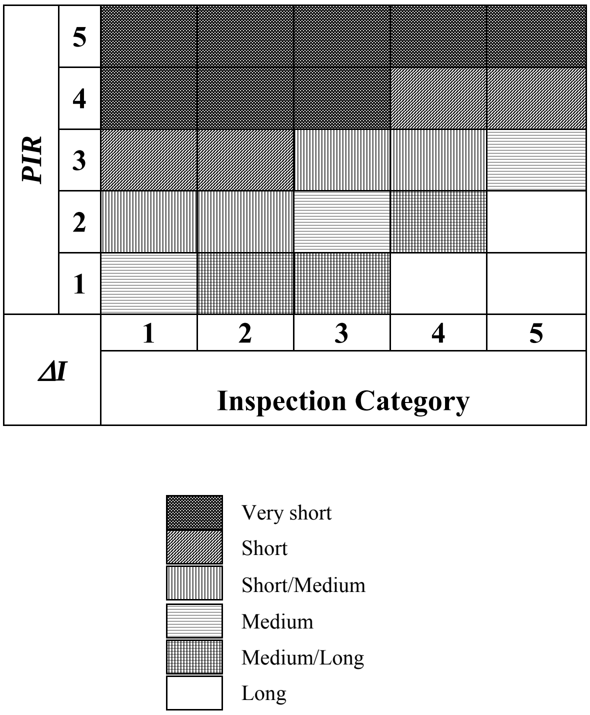
extent to be decided on-site,
** mesh of measurement to be decided on-site

DM	dimensional examination
ET	eddy currents
MT	magnetic particles
PT	dye penetrants
RT	radiographic test
ST	replication
UT	ultrasonic test
UTS	thickness examination
VT	visual testing

Table 5 - Global Risk Level

Creep Damage Level					
	V	-	-	-	-
	IV	-	-	-	-
	III	PIR 3	PIR 3	PIR 4	PIR 5
	II	PIR 2	PIR 2	PIR 3	PIR 3
	I	PIR 1	PIR 1	PIR 1	PIR 1
PIR		A	B	C	D
		Weld Type			

Table 6 – Inspection intervals (ΔI)



9. Conclusions

Non-destructive testing represent a fundamental tool for assessing the integrity of pressure vessels and boilers subject to creep both during design and service.

NDT constitute an important tool during service to assess material degradation and integrity. From ISPESL experience it is clear that replicas play a fundamental role in life assessment procedures of creep operated components. It could be very useful to compare result of replicas during service inspections with replicas performed during the fabrication stage in order to assess material ageing evolution. For this reason the new draft of "creep amendments" of EN 13445 regarding unfired pressure vessels is suggesting to perform replicas at the end of the fabrication stage together with high precision diameter measurements.

Some NDT techniques for creep damage detection are becoming more attractive: among them phased array methods seem to be very interesting for their ability to detect incipient creep damage, but for the time being they do not seem to be able to replace the replica examination.

High energy piping can be quickly inspected with AE or TOFD but a complete investigation of creep damage should include TOFD or Replicas.

Ultrasonic techniques are very interesting for detecting working temperature by oxide scale measurements or, alternatively, by hardness measurement or extractive replicas.

A very effective technique for material characterization of creep operated components is the “small-punch”, especially for what concerns FFS evaluations.
Very interesting methods for strain monitoring seem to be the SPICA method and laser profilometry, both of very straightforward application.
As shown in this paper NDT also play a fundamental role in the RBI procedure for the determination of re-inspection intervals and in the FFS procedure to be used in case of creep cracks.

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