

Weld Root Measurement by ToFD for Inspection of Flow-Accelerated Corrosion Susceptible Welds

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Abstract:

After the Mihama accident (2004), EDF re-examined its existing inspection strategy of Flow-Accelerated Corrosion (FAC) for the secondary loop of Nuclear Power Plants. Welds have been identified as a weak point and the necessity to develop or adapt a method to inspect them have arisen. On the basis of the inventory of the welds' inspections defect type and shape has been defined. Since 2006 the ultrasonic technique ToFD has been tested and in 2009 confirmed to locate and dimension weld root corrosion. After some thousand welds inspected results show that weld root and its neighborhood is a privilege zone for FAC degradation, combining chemical and hydrodynamic differences probably increasing FAC rate.

Keywords: time of flight diffraction (ToFD), thickness measurement, flow-accelerated corrosion (FAC), weld root degradation

1. Introduction

Corrosion affecting weld root and heat affected zone can lead to thickness loss. Different nondestructive techniques can be used to dimension and locate these losses. One of them is the ultrasonic technique time of flight diffraction (ToFD), which enables inspection « into » the weld. EDF is applying a method based on ToFD to make thickness measurement and dimension degradation caused by flow-accelerated corrosion in Nuclear Power Plant (NNP).

2. Weld susceptible to flow-accelerated corrosion

2.1. Flow-Accelerated Corrosion

Flow Accelerated Corrosion (FAC) is very effective for nuclear and fossil power plant carbon and low alloy steel. Occurring for liquid water or wet steam flow with temperature range between 75 & 300°C it is particularly active around 150°C. Additionally this phenomenon depends on different parameters, not only chemical - as it is a chemical phenomenon - but also on hydrodynamics (flow, isometrics and turbulences), physicals (quality of steam) and thermodynamics (temperature, pressure).

Recent accidents have pointed to this risk and one of the latest, Mihama (Japan 2004, 4 fatalities), has caused EDF to evaluate its own FAC surveillance strategy. This global strategy is based on a National Maintenance Rule which has been written by the corporate engineering level of EDF called "RNM" and applied by every Nuclear Power Plant operator of the EDF fleet. The RNM is mainly based on the use of the FAC-prediction software "BRT-CICERO™" as well as on specific actions for the lines or elements that are not modeled in the software.

Since 2000 every French nuclear power plants (NNPs) has its susceptible systems modeled in software, BRT-CICERO™, which enables the prediction of thickness losses depending on the following parameters :

- geometry (isometrics) and hydrodynamics (pipes fittings),
- chemical (water conditioning),
- thermodynamics (temperature, pressure),
- alloy content of steel pipes

One of the most important setting is the chromium content of the elements : for example, 0,15% Cr can divide FAC rate by 4. When content value is not known, it can be easily measured using X-Ray fluorescence (EDF recommendation) on each components of each lines. After the Mihama accident, one of the states pin-pointed by the survey made with the EDF fleet (58 NPPs) has been that welds were not included in the scope of the inspected elements.

2.2. Weld root degradation shape

On this basis an important study was led to analyze various morphologies of affected weld roots due to FAC to identify the level of criticality and the geometry of the defects [1]. It was established that:

- The intensity of the degradation is directly proportional to the content of chemicals of alloys in weld deposit material,
- The alloy content (especially chromium) of adjacent components does not allow to transfer a protection towards the FAC to the weld, even for high contents
- However, it was observed that the contents in chromium and the other alloys of the adjacent components will influence the geometry of the degraded welds.

The typical forms of observed degradations can be summed up by the Figure 1. If omitted when referring to affection, damage, degradation or susceptibility in the following only FAC phenomenon is meant and considered.

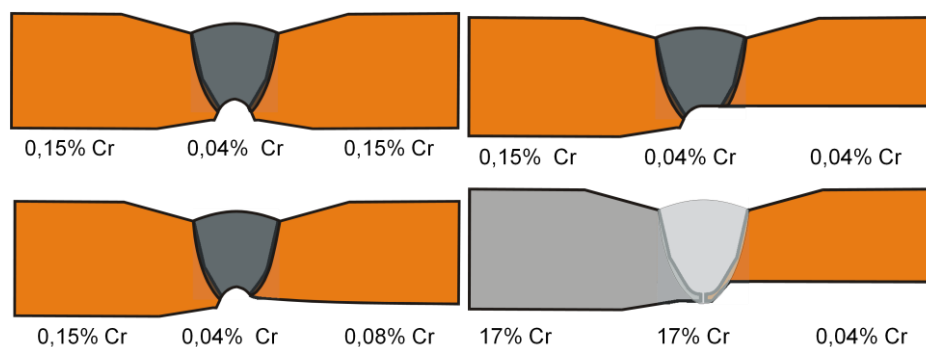


Figure 1. Various shapes of degradation according to the content in chromium

As can be seen in Figure 2, FAC susceptible weld beads can show a selective attack of low chromium containing welds have even been observed on high chromium containing components. This configuration is the worst configuration for maintenance because high chromium containing pipes are not susceptible and so, not inspected. The weld attack can then remain undetected. However, when the component is manufactured from low chromium containing material, the wear measured on the component near the weld can bring the weld attack to the inspector's attention.

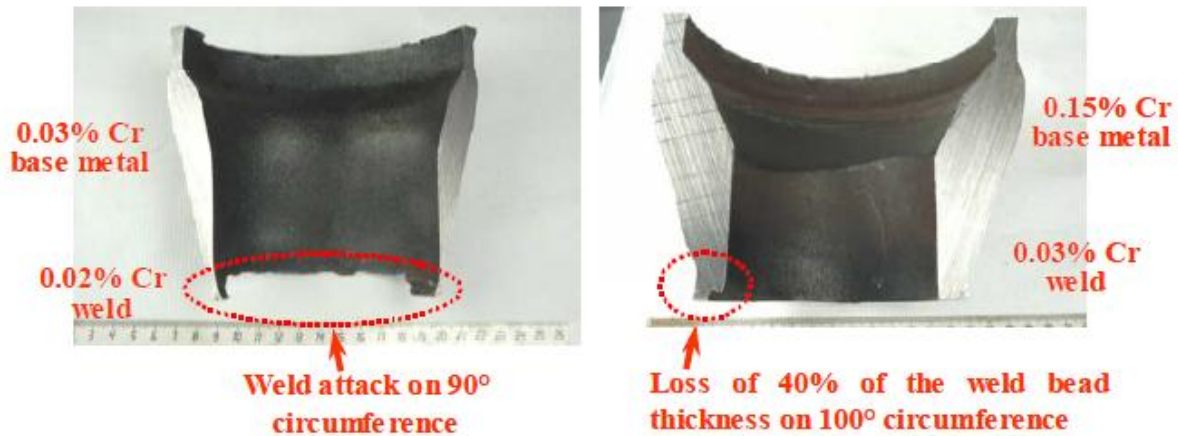


Figure 2. Weld attack between valves and expanders from Fessenheim unit 2 - 2001

Carbon steel welds of the examined components have a low mean chromium content (0.02% to 0.065% Cr) which is in agreement with the fact that welding rods generally don't contain any chromium. Moreover it seems that welds are sometimes not protected by the chromium contained in the base metal. Welding dilution in the root weld seems not always sufficient to protect it from FAC even despite high chromium content of the adjacent component. Chromium diffusion from the base metal to the weld is observed but limited to a distance shorter than 250 μm . As a consequence, we can say that all the carbon steel welds can potentially be affected by FAC.

FAC rates can be locally higher because of turbulences or fluid acceleration: presence of an obstacle in the stream, change of fluid flow orientation, excess penetration of weld not affected (i.e. dissimilar metal welds or some carbon steel welds), etc. As a consequence a leakage can occur in the upstream or downstream pipe susceptible to FAC and seemingly at a short distance from the weld root side. Degradation of the weld root or of the heat affected zone (HAZ) can also occur (Figure 3). The same local hydrodynamic phenomenon probably also affects two pipes with very different chromium contents welded together.

Because of different FAC rates a step can be created by loss of thickness which then causes turbulences. The step height activating this phenomenon is still to be determined.

For the same chromium content of a weld bead damage of the weld will be greater if the component is itself damaged (Figure 3). Finally, even if adjacent components are non-affected root can be corroded up to 50% of its nominal thickness.



Figure 3. Affected weld with uncentered degradation

To sum up the researched defect can be:

- Not necessarily in the center of the root,
- Quite localized
- Generalized to the HAZ

According to all these observations, to dimension and locate this defect type an ultrasound (US) technique has been applied: ToFD (Time of Flight of Diffraction).

3. ToFD for thickness measurement

3.1. Principle

Based on the principle of the diffraction of an incoming US wave by a defect, it was first developed for sizing of defect in a weld [2]. Unlike normal US, amplitudes are not used as sizing criteria: the time of flight difference of direct, reflected/diffracted waves is used as depicted in Figure 4.

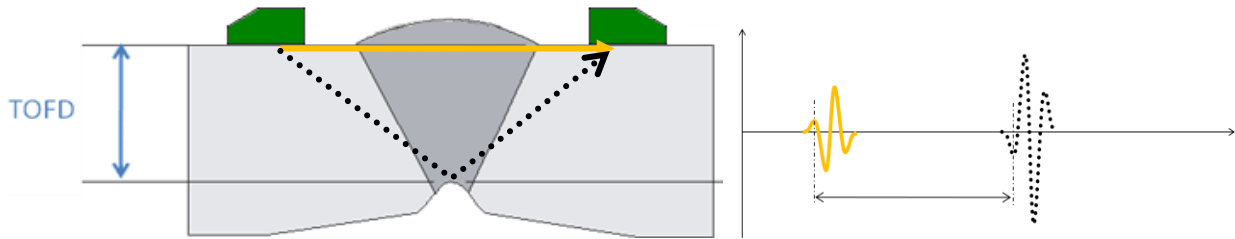


Figure 4. Principle of ToFD : US paths and corresponding A-Scan (time vs amplitude)

A probe sends a compression (longitudinal) wave (~ 5920 m/s in steels) on a wide angle, with a preferred orientation, in the material. A part of the US wave travels on the shortest path, i.e. under the surface, till the receiver: the Lateral Wave (LW orange/full line in figure 4). The second first arriving wave is the first to meet a discontinuity in the material, i.e. bottom, root corrosion or eventually defect. In the latter case, a new US wave is re-emitted: a diffracted wave. For FAC affected weld root a reflexion phenomenon is rather observed. In both cases time of flight is used to define the depth of the defect or the sizing of weld root. Calculation principle is shown in Figure 5. Additionally others reflexions and mode-converted waves arriving later can be used for interpretation [3]. Difference in velocities and uncertainties of origin makes it complex to use for calculation.

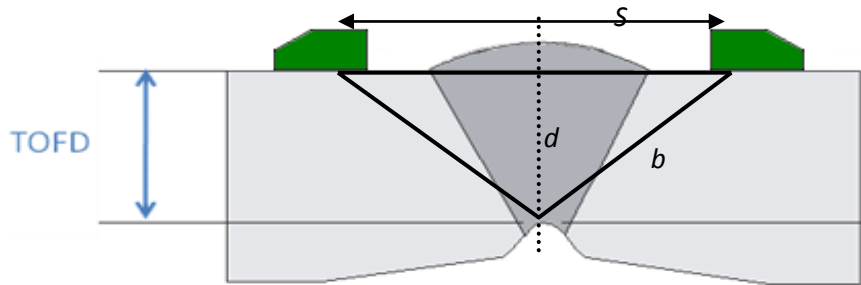


Figure 5. Principle of depth/thickness measurement

The Probe Center Separation (PCS) is set before the measurement and $S = \text{PCS}/2$, depth is then:

$$d = \sqrt{b^2 - S^2} \quad (1)$$

Considering times of flight:

$$d = \sqrt{\frac{(c \cdot t_{RR})^2}{4} - S^2} \quad (2)$$

Where $c = 5920 \text{ m.s}^{-1}$ is the velocity of longitudinal wave and t_{RR} is time of flight for signal from probe 1 to probe 2 with considering Root Reflexion.

US ToFD is implemented with an encoder that enables the recording of a A-Scan for every position of the circumferential weld. We finally have a thickness measurement on every position around the weld as shown in Figure 6.

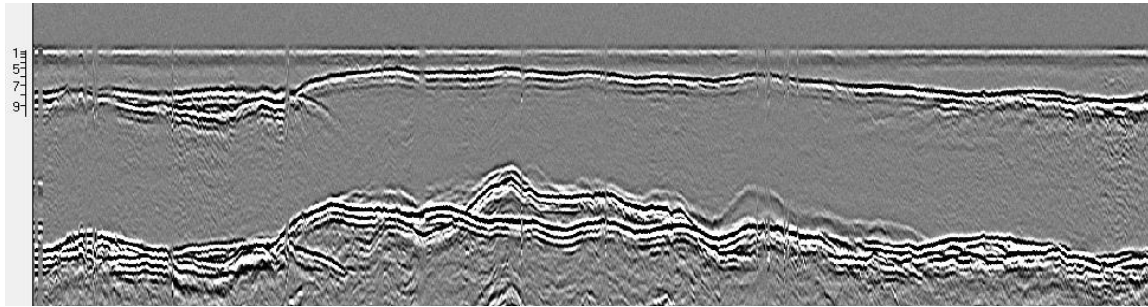


Figure 6. ToFD Acquisition with thickness calculated

3.2. ToFD on the Nuclear Power plant

3.2.1. Measurement procedure

Considering the way thickness is calculated, and the fact that root degradation is not necessarily centered (as in Figure 3), other parallel scans must be performed to avoid underestimated degradation as illustrated in Figure 7.

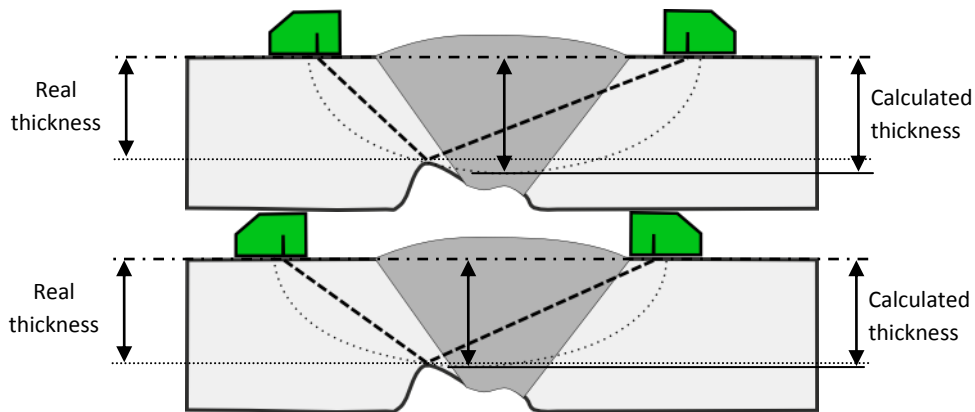


Figure 7. Uncentered degradation and thickness mismeasurement: center scan (up) & scan with offset (down)

It is assumed in the use of formula (2) that degradation is centered on the axis weld. FAC is a generalised corrosion and the case illustrated above could be real, i.e. if HAZ is affected the adjacent component or the weld will be affected as well.

Additionally to a center scan, two scans are performed with upstream and downstream offsets versus fluid flow. Should these additional acquisitions not be possible, a conservative measurement calculation is applied with a worst case scenario based on the remaining scan data. Finally to catch degradation on adjacent components, straight beam probes are used with recording system to get the position of a minimum thickness value near the weld.

To sum up, a ToFD inspections is realized accordind to:

- Thickness measurement on the weld on the base of the minimum of three ToFD scans, centered and with offsets ;
- Thickness measurement on adjacent components to detect FAC near the weld.

Using all these scans allow to find out:

- Minimum thickness of the weld (not including the specific thickness of the weld cap)
- Minimum thickness values on adjacent components

The same procedure can be applied by different contractors for EDF and EDF opt for a conservative tolerance for the measurement in order to have results with uncertainty not depending on the device they use. The global uncertainty is of ± 0.5 mm. A data record for every area is done, enabling to position and compare results with a next measurement.

3.2.2. Results

An extraction of 360 inspections (Figure 8) clearly shows that minimum thickness (light-blue upper part) is often measured in the weld. In some cases it can even be detected in linked components or in both. *URT* (purple) refers to an under thickness measurement, which is the limit to trigger repairs or other investigations.

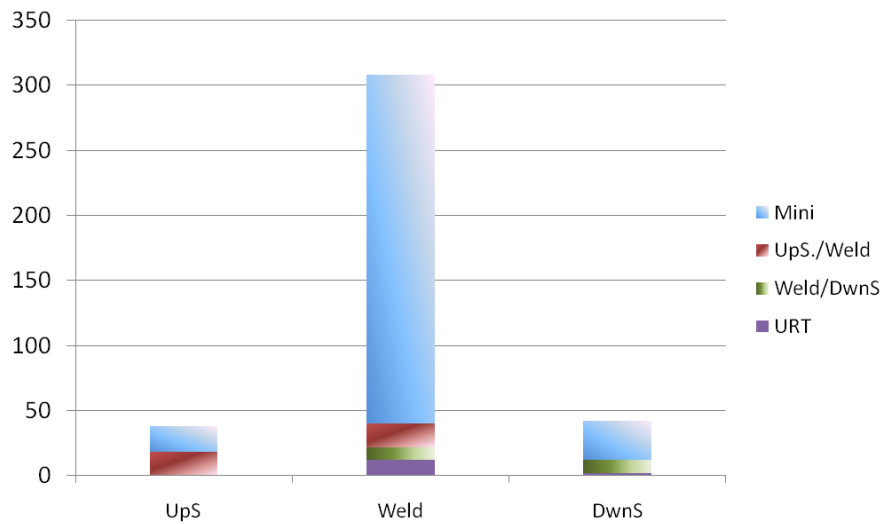


Figure 8. Proportions of inspected welds with minimum thickness

On the same extraction, thicknesses measured are sorted depending on the difference between thickness in the weld and minimum thickness of welded components:

$$difference = thickness_{weld} - thickness_{min\ component\ ts} \quad (3)$$

Hence positive values mean lower thickness measured in the weld. On the Figure 9 a central interval includes the uncertainty of measurement ± 0.5 mm. Minimal and maximal differences are respectively -3.6 and 4.5. On this criterion about half of the considered welds seem as affected as its neighbours. Values above 0.5 mm indicate that the trend of welds more affected than adjacent components is globally confirmed.

Moreover measurement on up- or downstream components does not give any information on the weld health. The contrary is true as well: for some cases, secure values of thickness of the weld root can hide affected neighbour components. This has to be taken into account when considering a weld as inspected.

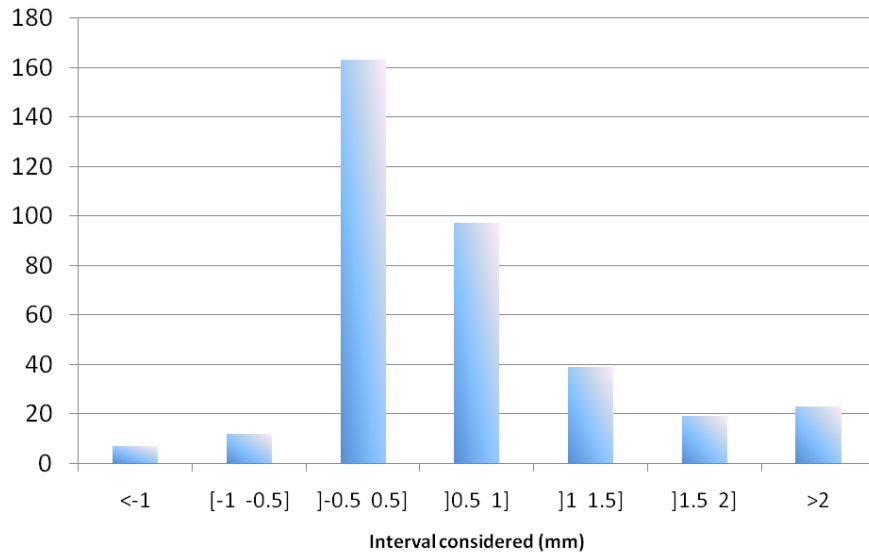


Figure 9. Difference between thickness measured in the weld and on welded components

Extreme values (< -1 et > 1) could be eventually linked to difference in alloy content or local highly turbulent flows (or both): excess of penetration, difference in FAC rates. Sometimes explanation is simple: i.e. supplied pipe had greater thickness than designed (documentation), stripping back during welding operation, etc.

Extreme values must be considered with their context to analyse apparently critical situations. This is one of the reasons why thickness measurements are performed on up- and downstream components as well.

3.2.3. Issues

Applying ToFD, a sensitive technique, on a zone where others classical testing had been performed pin point the problem of comparison: previous measurement cannot be directly compared leading to the question: has it not been seen or has it appeared during operating? Phased array should be used to identify indications detected by ToFD.

As a new technique using computing resources and results it implies this general questioning about how to keep system updated to read data and store it.

4. Conclusions

As explained in the beginning, FAC is highly depending on alloy content (chromium, molybdenum, copper) of the component. Welds with poor alloy contents are then very susceptible to this degradation type in NPP where operating conditions (water and steam, 75-300°C, etc) are triggering this phenomenon. Measurement results seem to confirm that a weld is generally more affected than its adjacent components. Minority cases of relatively high difference of thicknesses between weld and direct proximity must first be considered with context (wrong references, welding consequences, etc) and still can be examples of local particularity: excess penetration, high alloy content difference, hydrodynamics (valve, elbow), etc.

With this additional information, weld neighbourhood is the perfect place to observe a higher FAC rates linked to chromium (or other elements) content or influence of weld geometry.

Despite inspection on main components welds seem to be more affected by FAC than its adjacent neighbours making this weld root thickness measurement important. Complex configurations have still to be studied to enlarge the control panel. Gathering more inspection results will enable a better understanding of local chemical and geometrical influence.

References

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