HIGH CYCLE THERMAL FATIGUE FATHER EXPERIMENT: NON DESTRUCTIVE AND METALLOGRAPHIC EXAMINATIONS

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ABSTRACT

In May 1998, a leak (30 m^3/h) occurred in the reactor heat removal system (RHRS) of the Civaux 1 French power plant (PWR type N4, 1400 MWe) which was then in a hot shutdown situation [1,2]. A 180 mm through-wall crack was found in a 304L austenitic stainless steel elbow in a mixing area of high and low temperature fluids. The major root cause for cracking was identified as high cycle thermal fatigue (HCTF). The cracks were found in the mixing tees and at the roots of welds in mixing areas. The presence of ground surface finishes and of geometrical discontinuities like weld roots was associated to fatigue damage. For the new RHRS mixing zones of N4 plants, decision was then taken to suppress welds or locate them away from mixing area and to improve the surface condition.

To reproduce the HCTF phenomenon occurring in mixing zones, a representative endurance thermal fatigue test named "FATHER" was performed by CEA under an EDF/CEA/AREVA agreement [3]. The test lasted 300 hours. It was performed on a 304L stainless steel mixing zone of 7 mm thick and 6" diameter with a temperature difference of 160°C between cold and hot fluids. Different internal surface finishes were introduced in the test mock-up: coarse and fine grinding, industrial polishing, as extruded surfaces and as welded or flushed joints.

This paper proposes to present the numerous non destructive examinations (NDE) which were performed during and after the endurance fatigue test like ultrasonic examinations or dye liquid penetrant inspections. They led to the observation of many small thermal fatigue cracks located near as welded joints, on ground surfaces and on unpolished flushed welds. Cracks were not observed on industrially polished surfaces reproduced in straight piping sections or in flushed plus polished welds.

This paper also focuses on the detailed metallographic examinations which were performed after the endurance test. These ones have been carried out after having axially cut the mock-up in two symmetric half parts and machined sampling plates containing HCTF cracks. In this way, more than 50 thermal fatigue cracks with depths of 100 to 1000µm were observed. Cracks initiate mainly on geometrical discontinuities like weld toes or grinding striations. Test results have allowed to improve and to validate methods and tools for predicting crack initiation in mixing zones. The FATHER experiment can be seen as a significant contribution for preventing the risk of HCTF in PWR equipment.

INTRODUCTION

In May 1998, a leak (30 m^3/h) occurred in the reactor heat removal system (RHRS) of the Civaux 1 French power plant (PWR type N4 – 1400 MWe) which was then in a hot shutdown situation [1,2]. A 180 mm through-wall crack was found in a 304L austenitic stainless steel elbow in a mixing area of high and low temperature fluids. French operating experience has shown that all RHRS mixing zones of N4, 900 and 1300 MWe PWRs were damaged in fatigue and replaced with improvement of the manufacturing [4]. For the RHRS mixing zones of the 58 French PWRs, generally small crack depths of maximum 2 to 3 mm were observed excepted for Saint Alban 2 (5 mm depth) and Civaux 1 (through crack of 10 mm depth) [5].

A large metallurgical examination program was performed on several damaged mixing zones and the analysis of metallurgical results or of the operating conditions showed that the main root cause of damage was high cycle thermal fatigue (HCTF) due to temperature fluctuations of fluid in the mixing zones. The cracks were found in the mixing tees and at the roots of welds in mixing areas. The presence of ground surface finishes and of geometrical discontinuities like weld roots was associated to fatigue damage. For the new RHRS mixing zones of N4 plants, decision was then taken to suppress welds or locate them away from mixing area and to improve the surface condition.

To reproduce the HCTF phenomenon occurring in mixing zones, a representative endurance thermal fatigue test named "FATHER" was performed by CEA under an EDF/CEA/AREVA agreement [3]. The test lasted 300 hours. It was performed on a 304L stainless steel mixing zone of 7 mm thick and 6" diameter with a temperature difference of 160°C between cold and hot fluids. Different internal surface finishes were introduced in the test mock-up: rough and fine grinding, industrial polishing, as extruded surfaces and as welded or flushed joints.

This paper proposes to present the numerous non destructive examinations (NDE) which were performed during and after the endurance fatigue test like ultrasonic examinations or dye liquid penetrant inspections. It also focuses on the detailed metallographic examinations which were performed after the endurance test. These ones have been carried out after having axially cut the mock-up in two symmetric half parts and machined sampling plates containing HCTF cracks.

DESCRIPTION OF THE FATHER EXPERIMENT

FATHER mock-up

The FATHER program [3] is an experimental study on mock-ups, close to real mixing tees in plants (RHR new configuration type), carried out by CEA under EDF/CEA/AREVA agreement. The mock-up is composed of an equal 6" T-junction and of its inlet and outlet branches made of AISI 304L austenitic stainless steel. The outlet branch is divided into three successive 300 mm straight pipes welded together. The welds between these 3 straight pipes and the tee have different surface finishes (Fig. 1).

The first two straight pipes of the outlet branch are divided into 5 sectors with polished, ground (Rt ~ 30µm for a fine polishing and > 50 µm for a coarse on) or as manufactured surface conditions (Rt ~ 30 to 50 µm). The sector width is close to 50 mm. The thickness is about 7 mm in the branches and about 20 mm in the T-junction.

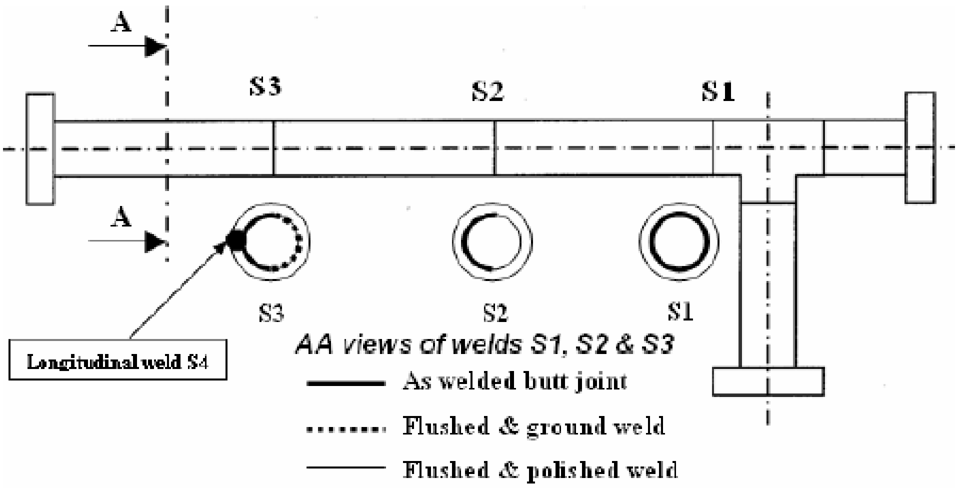

Fig. 1: FATHER mock-up - Description of the three welds

FATHER test program

The thermal-hydraulic conditions were defined with respect to the dimensionless numbers that drive the turbulence flow and the wall heat transfer in the RHR systems. In supplement the flow velocities of about 4 m/s in the inlet branches are close to those in RHR systems. The temperature difference between the cold and hot fluids was close to 160°C (204°C – 44°C) with a ratio of cold flow rate on the total flow rate of about 20%. The mock-up was attached to an 8 MW power facility.

To acquire knowledge in fluid and wall temperature fluctuations resulting from the mixing and to acquire data concerning the heat exchange between fluid and wall, a first mock-up was instrumented with sensors in the fluid and at the internal and external wall surfaces. A second one was only instrumented by strain gages at the external surface, for the purpose of surveying the stability of the conditions of the test. The objective was to submit the mock-up to the thermal fluctuations resulting from one set of thermal-hydraulics configurations (temperatures and flow rates at the inlets are maintained constant) in order to produce fatigue damage. These thermal-hydraulics tests produced a large database of fluid and wall temperature and of external surface strains.

The conditions of the damage (or endurance) test were reproduced during the thermal-hydraulics tests. The total endurance test duration was of 300 hours with four test sequences: 50h + 50h + 100h + 100h. Non Destructive Testing (NDT) was performed by AREVA on the endurance mock-up after each of the four test sequences and after the 300 hours of the endurance fatigue test. UT and liquid penetrant examinations leaded to the discovery of small cracks on ground surface finishes and at welds. Before cutting the FATHER mock-up, external manual ultrasonic testing (UT) and inner surface examinations were done. Last examinations were made with a photo-thermal camera.

After a longitudinal cut of the mock-up in two symmetric parts, the following NDT were performed:

- Automatic focused ultrasonic method,
- Long dye liquid penetrant examinations of inner surface of the 2 half parts with durations of 2 hours,
- Multi-elements ultrasonic method,
- Surface waves ultrasonic technique.

A good correlation was obtained between these four different NDT techniques. Main localizations of the thermal fatigue damage were near the as welded butt joints S1, S2 and S3 (Fig. 1).

DETAIL OF THE NON DESTRUCTIVE EXAMINATIONS

Before cutting the mock-up in two symmetric parts, manual ultrasonic examinations performed from the outer surface of the mock-up during the endurance fatigue test have shown that first thermal fatigue cracks appeared after a total cumulated time of 200 hours. These cracks initiate preferentially near the weld roots S1 or S2 (non flushed weld) and S3 (weld only flushed by grinding). Eight defects were for instance identified near the S2 as welded joint and some other indications appeared also on finely ground sectors (Rt = 25 to 30 µm) as well as on roughly ground sectors (Rt > 50 µm).

The FATHER mock-up was then cut in two symmetric parts in the longitudinal direction. One half of the mock-up contains the as welded half joints S1, S2 and S3 while the second half part contains the as welded half butt joint S1 and the flushed half welds S2 and S3. In this last half mock-up, S2 is flushed and polished while S3 is only flushed by grinding. Fig. 2 and 3 give the location of thermal fatigue cracks observed on the inner surface of the two half FATHER mock-up. These figures show also the location of sample plates taken in each of the two half mock-ups. These sample plates contain all the defect indications revealed by NDT examinations.

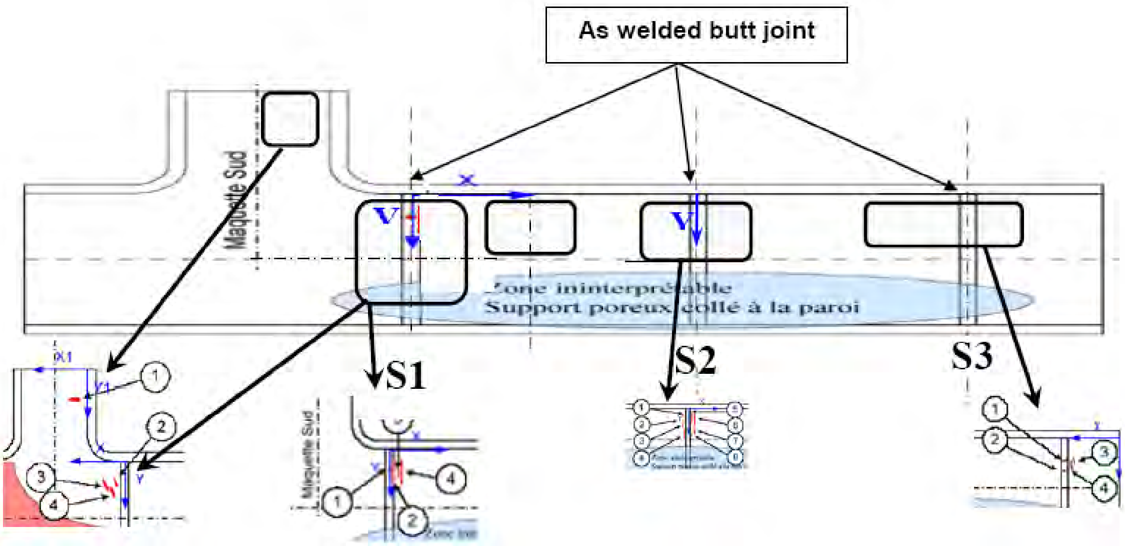

Fig. 2: First half mock-up containing the as welded butt joint S1, S2 and S3 - Long dye penetrant inspection results and location of plate samples containing all defect indications

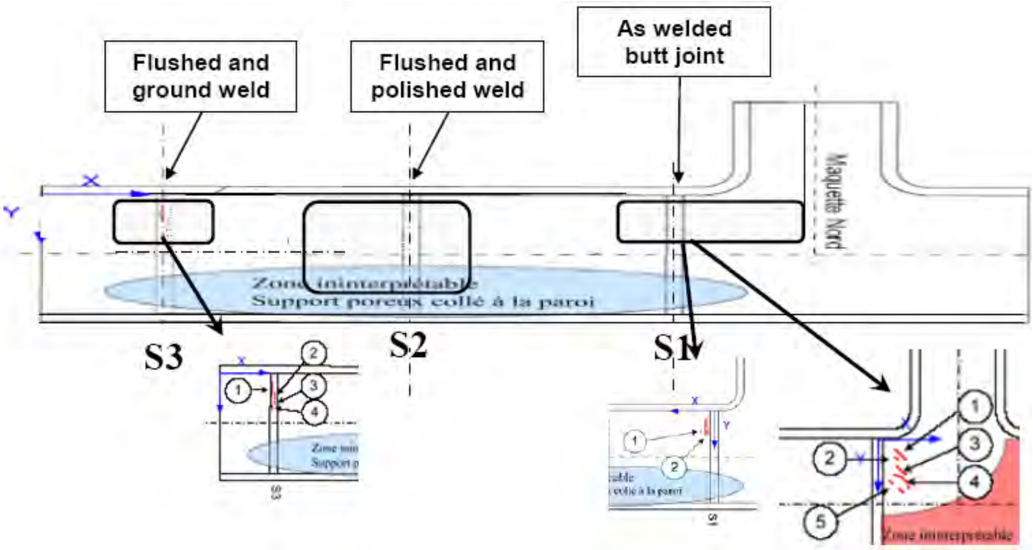

Fig. 3: Second half mock-up containing the as welded butt joint S1 and the flushed welds S2 and S3 – Long dye penetrant inspection results and location of plate samples containing all defect indications

After cutting by electro discharge machining of the eight sampling plates of the Fig. 2 and 3, the following non destructive testing were done on each of the sample plates:

- Long dye penetrant tests during about 2h,
- Ultrasonic examinations using focused transducers,
- Manual ultrasonic examinations from outer surfaces,
- Ultrasonic examinations using multiple transducers,
- Creeping waves ultrasonic examinations.

Generally, even if some techniques are more adapted to the examination of the sample plates, all these techniques are complementary and most of the same indications of defects have been observed during the endurance test. NDT results allowed to localize exactly all the defects and to take samples for metallographic examinations.

SIZING OF THE INDICATIONS BY METALLOGRAPHIC EXAMINATIONS

Sample plate taken in the S1 as welded butt joint (Fig. 2)

Metallographic cut shows that 6 cracks of depths varying from 120 to 630µm were seen near the S1 as welded joint in the straight pipe (Fig. 4a). Fig. 4b shows a micrograph of the crack number 6 initiated in the taper on an irregularity of the ground surface.

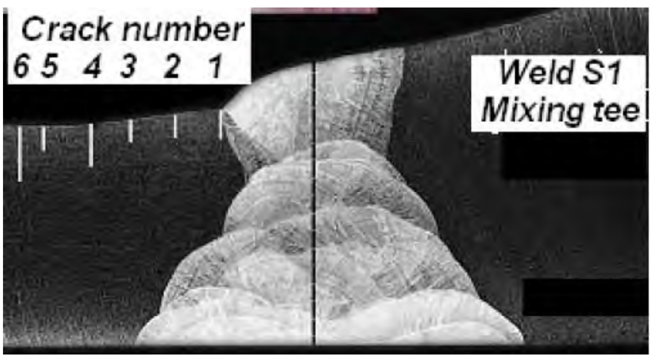

Fig. 4a: Cracks near the S1 as welded joint in the straight pipe

Fig. 4b: Crack 6 (S1 as welded joint)

Sample plate taken between S1 and S2 (Fig. 2)

Metallographic cuts in the ground sector between S1 and S2 show the presence of 7 parallel cracks with depths varying from 100 to 750µm, all initiating from bottom of grinding striations (Fig. 5).

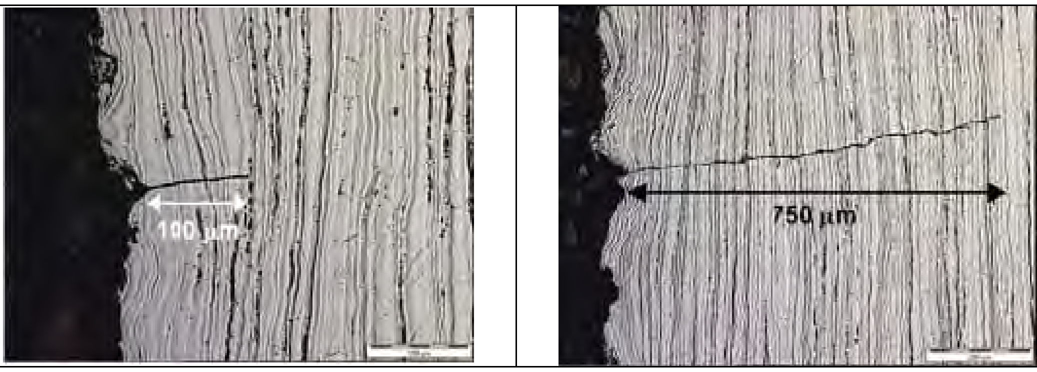

Fig. 5: Typical thermal fatigue cracks located in the ground sector between welds S1 and S2

Sample plate taken in the S2 as welded butt joint (Fig. 2)

This S2 sample plate contains 8 indications of cracks revealed by NDT examinations (UT and dye liquid penetrant test). Five metallographic cuts have been done for illustrating the 8 indications reported on Fig. 6. Fig. 7a shows the results of the metallographic cut number 4 made through the defects number 4 and 8. This metallographic cut number 4 revealed the presence of 11 defects instead of the two indications 4 and 8 seen after NDT inspections. However, the depths of these 2 cracks 4 and 8 are the most important of the 11 defects seen on the metallographic cut number 4. Their depths are respectively equal to 800 and 1000µm. It appears that little cracks are not systematically detected by NDT methods. Fig. 7b gives a view of the deeper crack observed on the metallographic cut Nb 4 of the S2 as welded joint.

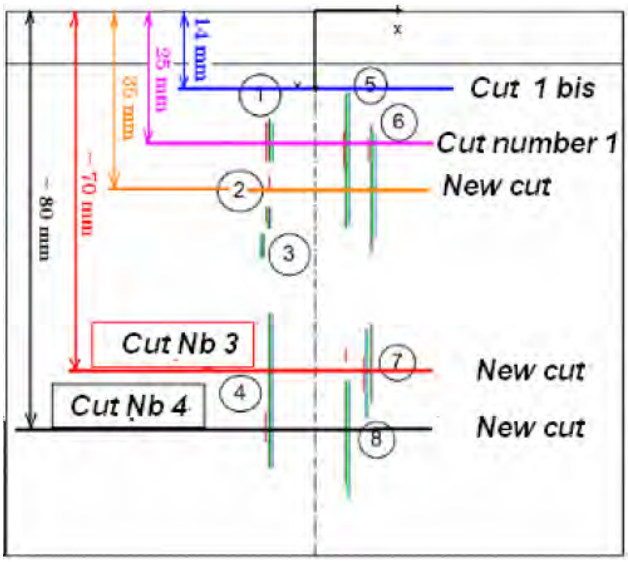

Fig. 6: Various NDT examinations results (UT & dye penetrant) of the S2 as welded joint sample

Fig. 7a: S2 weld butt joint / Metallographic cut Nb 4

Fig. 7b: Crack 8

Sample plate taken in the S3 as welded butt joint (Fig. 2)

Metallographic cut shows that 10 cracks are located near the S3 as welded butt joint (Fig. 8). These thermal fatigue cracks initiate just at the weld toe and also in the ground tapers on each side of the weld bead. Fig. 9 shows that cracks initiate at the weld toe or in the tapers on surface irregularities. Surface finish presents some irregularities and thermal fatigue cracks initiate preferentially on these irregularities.

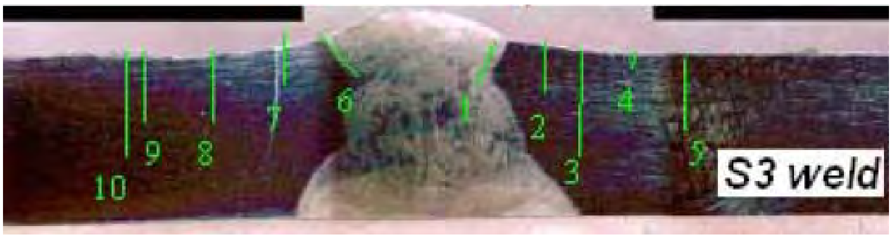

Fig. 8: S3 as welded butt joint (not flushed)

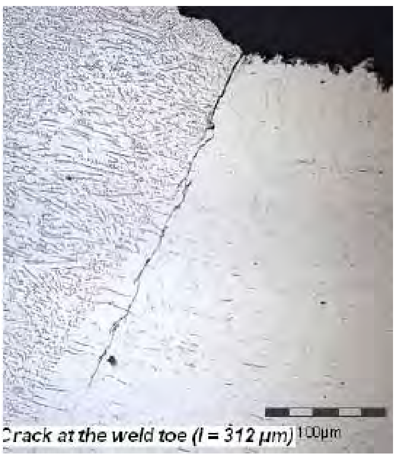

Fig. 9: Example of cracks in the S3 as welded sample

Sample plate taken in the S1 as welded butt joint (Fig. 3)

On this sample plate, 5 cracks have been observed in the S1 weld taper on the T-junction side with depths of 500 to 920µm (Fig. 10a). One thermal fatigue crack of 900µm initiates near the weld toe (Fig. 10b) and 6 other fatigue cracks with depths of 100 to 800µm were located near the S1 weld root. All thermal fatigue cracks are oriented in the circumferential direction and follow directions of grinding striations or of weld toes.

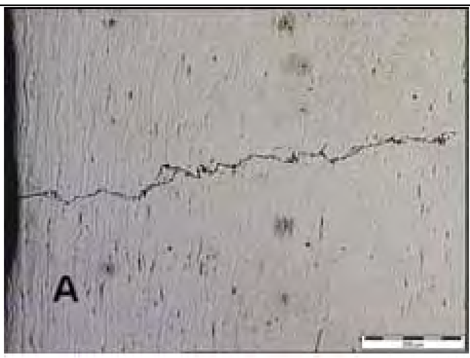

Fig. 10a: Crack of 900µm near the S1 weld root

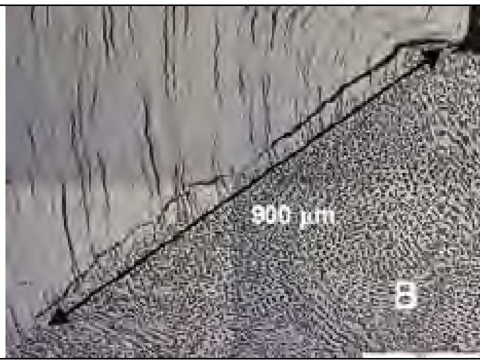

Fig.10b: Crack of 900µm at the S1 weld toe

Sample plate in the weld S2 (flushed & polished side) (Fig. 3)

No indications have been seen during NDT examinations of this polished sample plate. One metallographic cut have been done perpendicularly to the weld S2 in the flushed and polished area, and no thermal fatigue cracks were seen.

Sample plate in the weld S3 (flushed & ground side) (Fig. 3)

Metallographic cut shows that 7 fatigue cracks are located in the flushed and ground area of the S3 weld (Fig. 11a). These fatigue cracks are particularly fine and initiate on irregularities of the inner surface. Fig 11b gives a view of the crack number 5. It shows that surface finish of the flushed and ground weld S3 presents inner surface irregularities and cracks initiate on these irregularities.

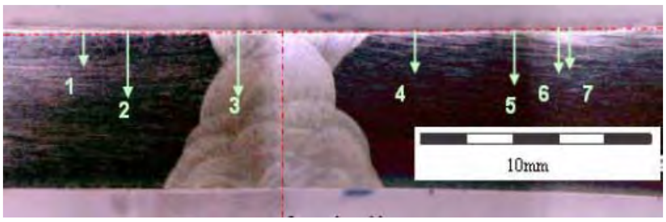

Fig. 11a: Cracks in the flushed and ground weld S3

Fig. 11b: Crack 5 (flushed & ground weld S3)

Conclusions on metallographic examinations

NDT and metallographic examinations of 8 sample plates taken from the two FATHER half mock-ups have shown that about 50 cracks with depths varying from 100 to 1000µm have been observed. This mock-up was submitted to a 300h thermal fatigue endurance test at a temperature difference of 160°C between cold and hot fluids.

The main conclusions on the localization of the thermal fatigue cracks are the following:

- Cracks initiate at weld toes and in ground tapers,
- Cracks initiate on geometrical discontinuities or on grinding irregularities,
- Cracks can be located in straight sections on locally ground surfaces and on unpolished flushed welds,
- No thermal fatigue cracks are observed in polished straight sections and in flushed and polished weld.

CONCLUSIONS

More than 50 thermal fatigue cracks with depths of 100 to 1000µm were observed in the FATHER mock-up and cracks initiate mainly on geometrical discontinuities like weld toes or grinding striations.

The FATHER test results have also allowed to improve and to validate methods and tools for predicting crack initiation in mixing zones [6-8]. This FATHER experiment can be seen as a significant contribution for preventing the risk of High Cycle Fatigue in PWR equipment.

In order to improve the fatigue resistance of RHRS mixing zones of EPR^{TM} power plants, manufacturing improvement as removal of weld roots and fine polishing of internal surface of new austenitic stainless steel components are now implemented for increasing lifetime [9]. New EPR^{TM} RHRS mixing zones are now forged 316L austenitic stainless steel components without welds and with inner surfaces that are polished in order to obtain roughness Rt lower than 15µm and to have residual stresses typically lower than + 100 MPa.

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