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Feasibility Analysis for Repair of Large Diameter Hydro Turbine Shaft Based on Weldability Test and Welding Cycle Simulation

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Abstract. Turbine and generator rotors and shafts undergo high stresses during regular working life and, from a safety and operational aspect, are the most significant components of a power generation system. Depending on the appropriate operating conditions, like temperature and/or corrosion the, shafts can be fabricated out of low/high alloy heat resistance material or of low alloyed, highly toughened material for different application. Despite known good practice and developed operation procedures, the failures of shafts sometimes occur. The right and well-defined failure analysis is the basis for feasibility analysis of repair method in the power generating industry. The analysis of direct and indirect costs of repair after the failure analysis as well as the analysis of the repair and post-repair conditions of the repaired element is the vital for decision on the key question. Is it possible to repair this element and what is the optimal repair strategy?
This paper compares and analyses two approaches, by weldability analysis and weld cycle simulation, in order to determine welding feasibility analysis of cracked hydro turbine shafts.

Introduction

The key pieces of hydroelectric equipment such as turbines, pumps, generators, generator motors, transformers etc. are well-known for their longevity. Once installed and operating correctly they diligently work for what appears to be an endless operating life compared with their coal and other renewable alternatives. This apparent immortality is further enhanced by regular and systematic maintenance but even in the most demanding conditions. The hydroelectric equipment is also known for relatively low cost little preventative maintenance, compared to coal and nuclear power plants.

Gathering information about cracks and failures of rotor shafts is generally kept confidential by the power plant management and by the machine manufacturer; therefore, not all the cases have been reported and analyzed in literature [1]. Many of such cases were solved by repair methods with underlying proprietary information. Serious problems are mainly expected high head plants having high water fall exceeding 250m, caused by high water pressures, pressure variations and high-water speeds. Therefore, catastrophic failures in hydro-power plants are rare, mainly due to the fact that main problems during operation are related to cavitations, erosion and material defects. Moreover, adequate preventive maintenance and clearly defined overhaul procedures in a hydro-power plants significantly reduce failure occurrences [1, 2].

Detailed failure analysis of hydro turbine shaft is presented in paper [3]. Briefly, this paper describes the failure analysis of turbine generator shaft Kaplan's 28 MW bulb turbine. The bulb turbine horizontal shaft is shown on Fig. 1a, and zone with cracks on Fig 2b. The turbine shaft is made by joining the forged and cast parts by slag welding, Fig 2. The shaft is manufactured as hollow, housing a servomotor inside it, for shifting the runner blades. The flange, on which transition radius the crack occurred, is made of steel casting of 20GSL (20Mn5) designation, according to GOST 97-88 [4].

After 163 411 hours of exploitation, on one turbine, the sudden oil loss was observed from the control system. Total projected operating life for the subject shaft is 200 000 hours. Upon stopping the turbine and after visual inspection of all the spots where loss could have occurred a through-thickness crack was discovered of 2100 mm length, through which the turbine oil leaked from the runner servomotor chamber. The location of this crack was on the flange radius R80, from the cylindrical part of shaft towards the flange to which the runner is connected. After the failure, Fig. 3, the shaft was disassembled and flame cut for the inspecting the crack surfaces, Fig. 4. In Fig. 3, residues of the anticorrosive coating were detected as well as significant number of corrosion pits in the zone of R80 radius.

a) b)

Fig. 1. Disassembled turbine shaft with runner, a) Transition (fillet) zone with cracks b)

As a result of the failure analysis [3] the following conclusions emerges that shaft failure occurred due to the combination of several factors:

- Inappropriate corrosion protection in the zone of critical radius and lack of procedures of renewing corrosion protection of turbine shaft.
- Corrosion, i.e. corrosion fatigue due to ingress of river water through the sealing box.
- High stresses during start/stop cycles and during regular operating regime in the zone of R80 radius for “wet” environment.

The following suggestions emerged from this failure analysis:

- Redesign of the seal box in order to eliminate of water ingress into the shaft-flange transition zone,
- Redefining of procedures for periodical non-destructive inspection of the shaft-flange transition zone status, with increased frequency,
- Periodical renewal of the anticorrosive protection on the shaft flange, especially in the shaft-flange transition zone,
- Checking the possibility for redesign the transient radius for reducing the stress level in critical radius,
- Keeping the start/stop cycles at minimal values as it is possible, and
- Considering an improvement of general technical conditions of delivery for flange material upon a new commissioning.

The experimental result and results of numerical calculations from presented viewpoint [3], based on circumstantial evidences like the position and shape of cracks, identified as corrosion fatigue cracks [5, 6, 7] on transition radius, raised additional questions. First question is about differences in classical analytical calculation of shafts with numerical calculation and what is the magnitude of difference if exists and second, what was the triggering stress on radius for corrosion crack initiation. The answer on first question was well documented [8].

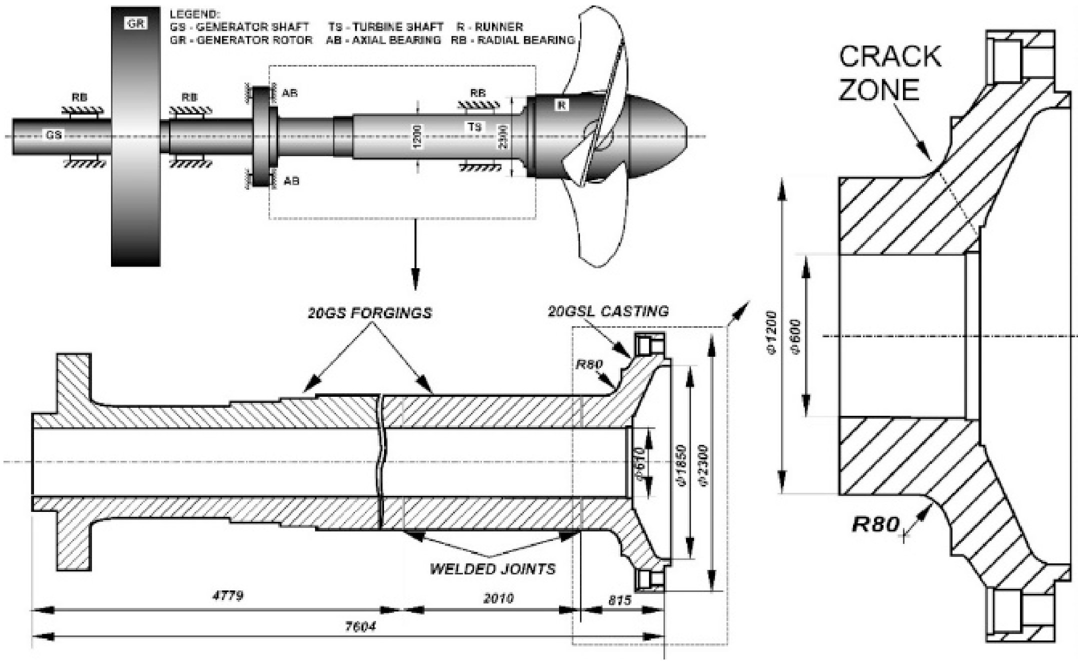


Fig. 2. Position of crack on general assembly of hydraulic turbine shaft the crack

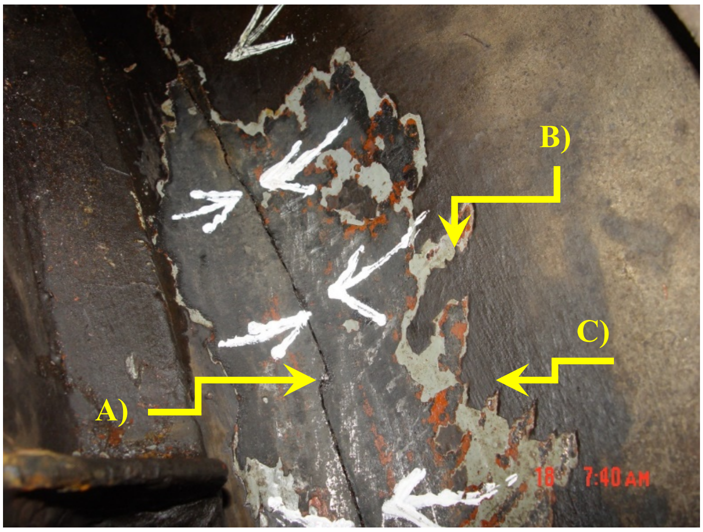


Fig. 3. Close view of the transient radius after detecting the crack a) main crack b) anti-corrosive protection layer c) oil residue on corrosion pits

Fig. 4. Zone of through wall crack on the hollow shaft; zones 1, 2 and 3 represents crack growth front of the through thickness crack, and the rest of the surface was flame cut surface

The detail explanation for the first question was presented with references [9] and the approximate answer on second question was presented on references [10,11], upon which the major aspects of failure analysis was examined. The additional research results, proved conclusions from failure analysis, noted previously, and emerge additional issues regarding design issues of this type of non-standard shafts. The key significance in understanding of the turbine failure mechanisms, and particularly identify turbine parts that are most susceptible to specific type of failure, emphasize need for different repair strategies [12, 13]. The analysis for each strategy requires thorough approach, and combination of simulation and experiment [13, 14], as a main goal of maximal reduction of a down time of repaired element. Daily costs of a down time in hydro power plants could be very high so exploring different strategies is significant for refurbishment cost reduction with decreasing risk of failure.

Turbine shafts and generator rotors undergo high stresses and, from an operability and safety aspect, are the most significant components of a turbine generator system. This is due to the fact that the any case of failure is linked with very long down time periods and significance costs

The majority of available references of turbine repair is related with welding. The term repair is commonly related to a remedial action taken after non-destructive (NDT) quality inspection, during the manufacturing stage or after maintenance routine inspection and during the in-service life of components. In common practice, the defects on power transmission elements, which might be a crack, void, lack of fusion in a weld joint or even degraded material, is, as a first step of remedy action, completely removed by excavation. The removed part of element, is filled with weld filler material compatible to the component's base material, following standard multi-pass welding procedures. For the majority of such cases, available in literature, whenever circumstances allow it, repair welding takes place in the workshop, according to original manufacturing standards [14,15], after shutting down equipment or isolating from the production process the part of the plant that contains the faulty component, e.g. piping, steam chests, headers, steam turbine blades, etc. [16]. In cases where an in-situ repair is necessary, as is the case of nuclear power plant piping components or even a pressure vessel wall, access to which is both limited and dangerous, special welding procedures, tailored to the specific situation, are developed. When carried out with minimum disruption of operations, repair welding is economically more attractive than conventional solutions, which in the manufacturing stage translate into discarding the faulty component, whereas during maintenance, require replacement of the component. Repair welding is becoming increasingly prevalent in the equally sensitive case of aircraft gas turbines, as a way of reducing the costs associated with blade and other component replacements [14].

The presented case study of cracked turbine with through crack was used to examine positive identification of cracks and study material of cracked turbine flange in-detail. However, on several more turbine shafts the cracks with different depth were found, which triggers repair or remedy action. There is no published repair practice in the hydro-power industry, applicable for cases similar to above presented, so the main challenge was:

1. Identification of root cause failure analysis;
2. NDT identification of position of size a position of cracks;
3. Detail analysis of weldability of material;
4. Analysis of material behavior on welding cycle simulator; and
5. Analysis of all available results.
6. Feasibility analysis of repair by welding.

The identification of failure analysis causes and identification of position and size of cracks achieved by NDT was presented by [3].

Weldability Analysis

Assessment of weldability through the application of analytical equations

The detail weldability analysis of flange material is costly and time consuming due to the fact it requires preparation of special specimens. Rough analysis of flange material is obtained by formulae, based on chemical composition, proposed by [17, 18]. The results showed that carbon equivalent as a partial measure of weldability was 0,45 which mean that the material of flange is conditionally weldable with preheating and post weld heat treatment. The results of maximal hardness calculation in heat-affected zone (HAZ) based on [19] formulae confirm previous results, and the result of such calculated hardness was 377 HV. The chemical composition of base material, 20GSL (20Mn5) steel casting, is shown in table 1 and mechanical properties in table 2.

Table 1. Chemical composition of base metal [3]

Analysis method/mass. %	C	Si	Mn	S	P	Ni	Cr	Mo	V	Al	W
OES	0,19	0,72	0,29	0,02	0,021	0,27	0,27	0,047	0,009	0,038	0,024

Table 2. Results of tensile tests and impact energy absorbed tests [3]

	Yield stress R_e (N/mm^2)	Tensile strength R_m (N/mm^2)	Elongation A_5 (%)	Contraction Z (%)	Energy absorb. $C_{V\,300/2}$ (J)
Values	314	525	15,3	39,2	58
According to standard GOST 977-88	min 294	min 540	min 18	min 30	min. 23,4 J

The consumable for welding of weldability specimens had the chemical composition shown in table 3.

Table 3. Chemical composition of consumable [21]

C %	Si %	Mn %	Cr %	Mo %	Ni %	Fe %
<0.10	<0.5	<5.0	<15.0	<1.0	rest	<10

Apart from determining the carbon equivalent for steels, it is also important to determine PCM, which is the crack parameter applied when calculating the parameter for the occurrence of cold cracks which is in use for low-alloy steels. Crack parameter considers only the chemical composition of the base material, in this case of a low-alloy steel. Apart from parameter equations for the assessment of resistance to cold cracking, equations for the assessment of proneness to hot cracking and cracking due to annealing, [20] are being used. Carbon equivalent is obtained through the use of known formulae. The results are shown at the table 4.

Table 4. Summary of results obtained by analytical equations, [21]

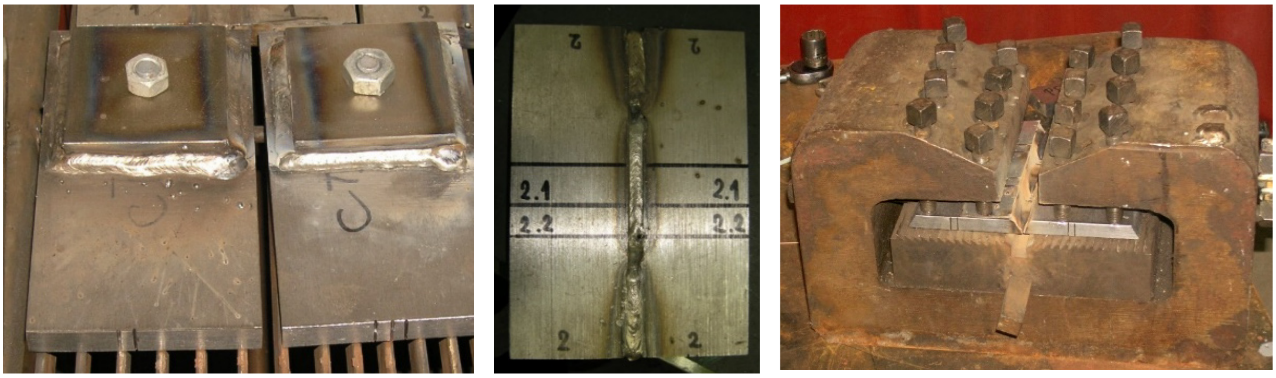
Carbon equivalent	Value	Reference values and assessment
CET (SEW 088-93)	0,33	Weldable, preheating required
CE BS 5135	0,45	Weldable, preheating and annealing required
PCM ANSI/AWS D1.1-96)	0,29	Weldable, preheating required
CEN JIS	0,47	Weldable, preheating and annealing required
HCS	2,15	When HCS > 4 prone to hot cracking

Weldability Test

The specimens, for weldability test in as welded condition, are shown on figure 5. Welding is done by 2222 Xuper NucleoTec with basic coating. Details about welding parameters can be found in [21]. The thickness of plates for weldability analysis was 15 mm.

The following weldability test were performed:

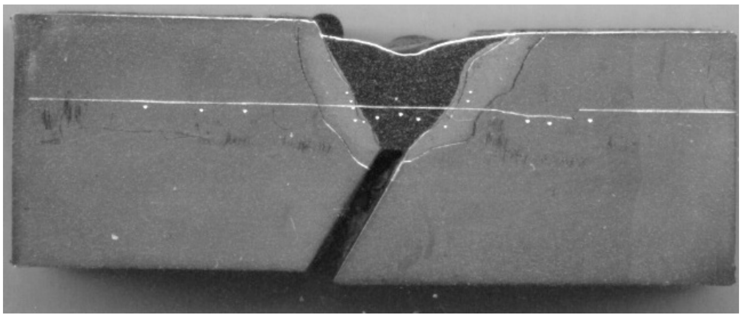
- Weldability cold crack test (Control thermal severity test - CTS,
- Japanese welding society, so called Y test, and
- Hot cracking (FISCO) test.



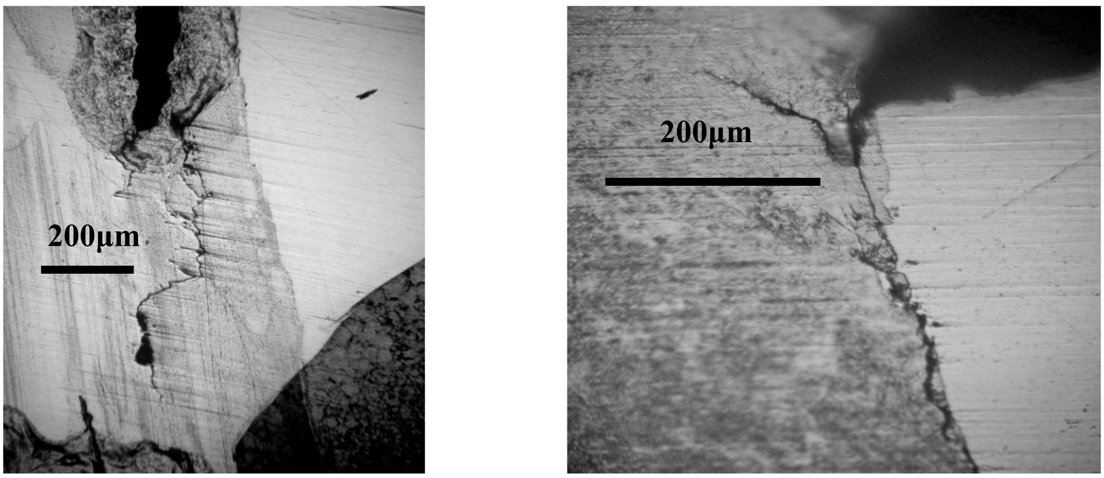
a) b) c)

Fig. 5. Weldability test on samples made from cracked turbine flange a) CTS test specimens b) Y test specimen c) FISCO test specimen restrained during welding

The results of all test were inconclusive, i.e. results were couldn't confirm good weldability of chosen consumable with base material. Some of the problems revealed during examination of specimens was shown of Fig 6. On Figure 6a) is shown cross section of Y test, and on figure 6b) and 6c) cracks in weld metal and HAZ, respectively. The combination of casting defects, shown on figure 7, and revealed cracks add more emphasize on potential problems of weldability, previously determined by chemical analysis. Additional recommendations of solving problems of crack occurrence was defined by [22].



a)



b) c)

Fig. 7. Some of cracks found on specimens a) cross-section of Y test welded plate b) cracks in weld metal c) cracks in HAZ

Weld Cycle Simulation

This problem can be avoided by using heat cycle simulators. Heat affected zone as a zone of local inhomogeneity due to geometry a microstructure, is obviously the most susceptible to crack initiation during welding. In presented case, the cracks in weld metal is not the issue, because impact toughness values above 120J, so the focus was shifted to HAZ. The thickness and size of surrounding material lead to very faster cooling conditions compared to weldability specimens. Therefore, specimens similar by dimension to Charpy specimens (11 x 11 x 60 mm) was set on heat cycle simulator. The specimens were heated uniformly at the rate of 200°C s^{-1} to peak temperatures (Tp) of 1300 °C. The cooling time between 800 and 500°C was 5, 10 and 45 seconds. The shape of curves is presented on Fig 8. The impact toughness and hardness for simulated specimens are show at the table 5. The significance of welding simulation is emphasized by obtaining real values of mechanical properties in heat affected zone. Advantage of weld cycle simulation, particularly in critical zone Δt8/5, is in reducing expensive experiments by possibility to calculate value Δt8/5 [23,24].

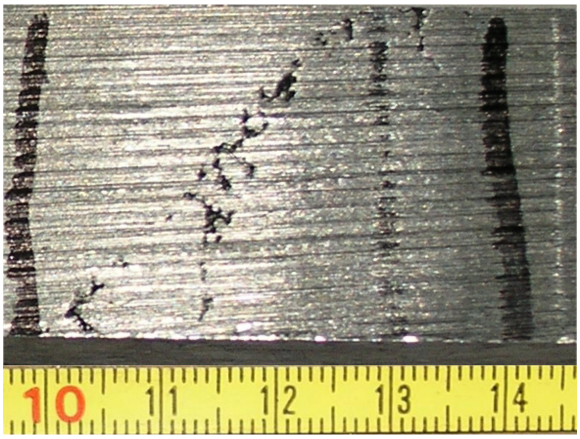


Fig. 7. Porosity in turbine shaft flange material

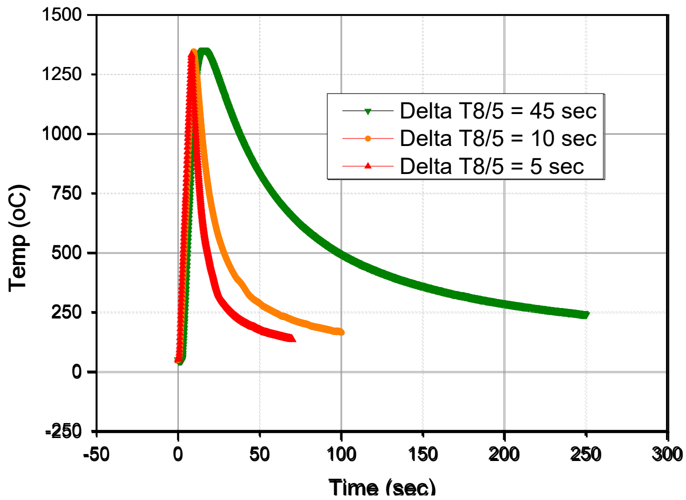


Fig. 8. Shape of simulated one-pass curves

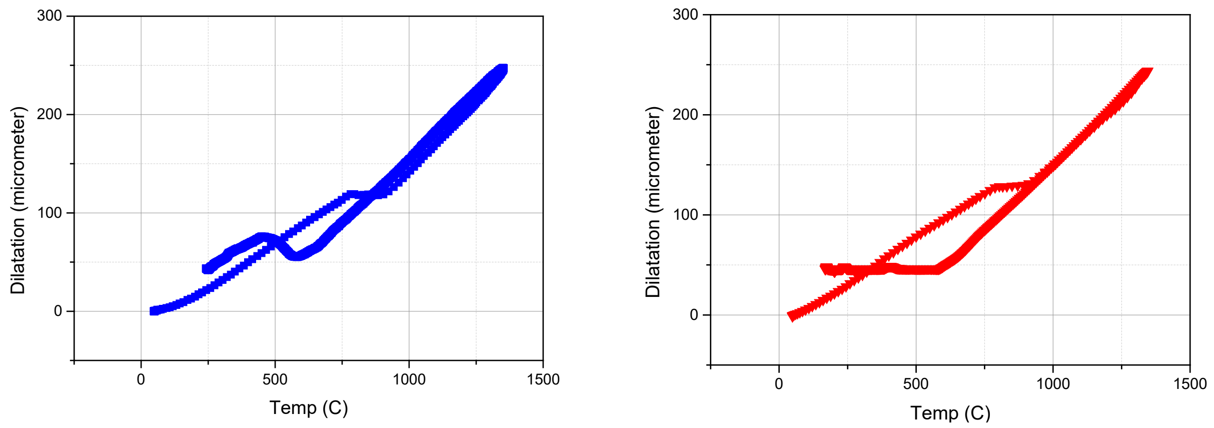
Table 5. Mechanical properties of simulated specimens*

$\Delta T_{8/5}$ (sec)	Impact toughness (J)	Hardness, HV, max value
5	**8,1**	**347**
10	**11,5**	**295**
45	**47,5**	**122**

*Average values of 10 simulated specimens

The result of dilatometric studies done on weld cycle simulator on the steel specimen is shown in Fig. 9

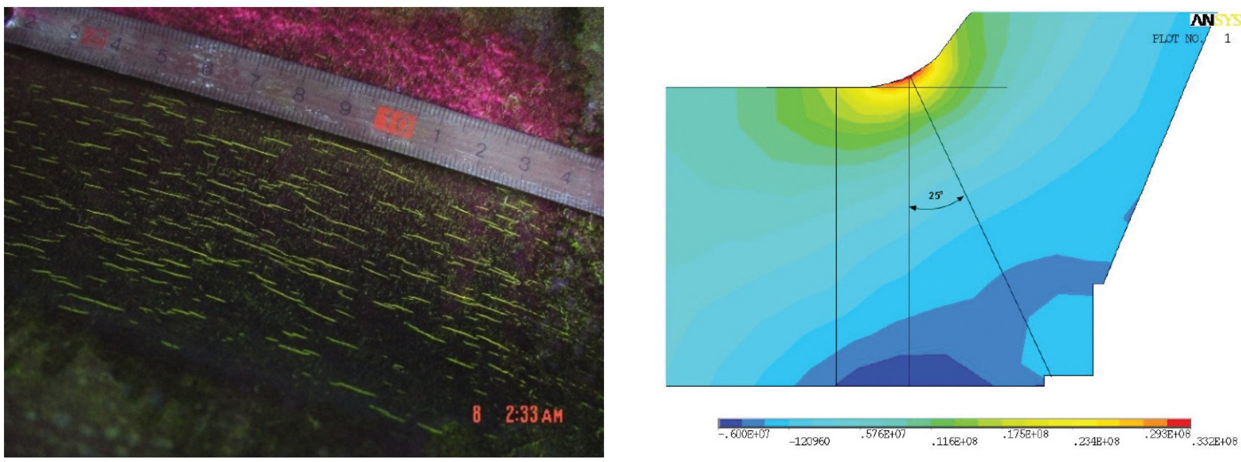
The results of weldability testing and welding cycle simulation does not directly encourage repair by welding as option. Welding is undoubtedly best repair strategy for many cases in power industry, but for this particular case it has questionable applicability. One of the main reasons for that is different operation time and conditions form turbine to turbine which disable finding universal solution for all cracked turbine shafts. This mean that reparation of each of cracked turbine must be analyzed separately from other cases of cracked turbine shafts.



a) b)

Fig. 9. Shape of dilatometric curves presented at figure a) $\Delta t_{8/5}$ = 45 sec, b) $\Delta t_{8/5}$ = 10 sec

The only common feature between all cases is zone of crack occurrence on transition radius, fig. 10a). The zone of crack occurrence is found by finite element analysis (FEA) as zone with maximal stresses, fig 10b). The matching between in situ NDT testing results and FEA analysis shows no significant difference. The comparison between FEA analysis and cracks on transition radius is shown on fig. 10. Therefore, the only criteria for repair strategy decision, for this case, was crack depth. For the "shallow" cracks (the cracks up to 15 mm, the grinding is better solution, and for the cracks deeper than 15 mm welding is more likely solution. Additional guidance for repair of fatigue loaded structures was defined by [23,24].



a) b)

Fig. 10. Comparison between NDT found cracks with zone of maximal stresses on transition radius obtained by FEM analysis

Conclusions

The comparative analysis of crack repair methods on the same type of turbine shaft offer unique chance to analyze different repair methods.

Presented problem of turbine shaft emphasize reliability and comprehensive approach as a key requirement for ensuring a reliable service life in the future. This means re-design of seal in order to minimize leaking of water on most stressed region – transition radius on flange, and choosing most suitable method of repair.

All above noted emphasize need for team work too, due to multidisciplinary or comprehensive approach toward of determining repair strategies. It is obvious from presented in this paper that team must be comprised by experts for machine design, numerical analysis, materials, welding, corrosion and machining. For example, influence of welding residual stresses on fatigue design of welded joints and components presents relatively unused strategy that can be combined with many other repair methods as defined in [25-27].

The main conclusion and lessons drawn from presented case study are:

- Every shaft cracking scenario has unique characteristics (depth, location, density) and service life history requiring a particular approach and different repair methodology;
- Repair methodology for any major component from power industry require comprehensive approach, based on reliable failure analysis;
- Stress analysis of failed element is one of the very basic elements not only during failure analysis phase, but also as an important fact in determination of method and scope of repair technology;
- Weldability testing and weld simulation are compatible and necessary, particularly in cases like presented one where difference between thickness of test plates used in weldability test and real element is significant.

The choice of repair strategy and feasibility analysis have many influential factors and may not be the same even for the same type of power transmission – in this case study the hydro turbine shafts.

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