Metallurgical and fatigue assessments of welds in cast welded hydraulic turbine runners

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Abstract. Decades of hydraulic turbine operation around the world have shown one undeniable fact; welded turbine runners can be prone to fatigue cracking, especially in the vicinity of welds. In this regard, three factors are essential to consider in runner fatigue assessments: (1) the runner’s design, which can induce stress concentrations in the fillets, (2) the casting process, which inherently creates defects such as shrinkage cavities and (3) the welding process, which induces significant residual stresses as well as a heat affected zone in the cast pieces near the interface with the filler metal. This study focuses on the latter, the welding process, with emphasis on the influence of the heat affected zone on the runner’s fatigue behavior. In a recently concluded study by a large research consortium in Montreal, the microstructure and fatigue crack propagation properties of a CA6NM runner weld heat affected zone were thoroughly investigated to find if this zone deteriorates the runner’s resistance to fatigue cracking. The main results showed that this zone’s intrinsic fatigue crack propagation resistance is only slightly lower than the unaffected base metal because of its somewhat finer martensitic microstructure leading to a less tortuous crack path. However, it was also confirmed that weld-induced residual stresses represent the dominant influencing factor regarding fatigue crack propagation, though post-weld heat treatments are usually very effective in reducing such residual stresses. This paper aims to further confirm, through a case study, that the weld-induced heat affected zone does not compromise the reliability of welded turbine runners when its fatigue crack propagation properties are considered in fatigue damage models.

1. Introduction
Welded hydraulic turbine runners are a challenge to design from a mechanical reliability point of view. Numerous factors enter the equation of predicting and ensuring the long lifetimes that are required of these components. Figure 1 schematically summarizes these factors and their interrelations. On one hand, intrinsic factors drive the runners’ mechanical resistance and can be grouped in three categories: (1) the runner’s design, (2) the casting elaboration process and (3) the welding process. These factors act in synergy to establish the runner’s static strength, cavitation resistance, erosion resistance, corrosion resistance, impact resistance, fracture toughness and/or fatigue resistance. The resulting intrinsic mechanical integrity is in mutual competition with extrinsic factors that solicit the runner and consume its lifetime. Extensive knowledge of key influencing factors is therefore necessary to design runners with sufficient intrinsic mechanical resistance to withstand the extrinsic solicitations for its entire intended operating lifetime.
This study is mainly concerned with the assessment of a specific intrinsic factor, namely the influence of the welding process on the fatigue and fracture resistance of hydraulic runners made of cast martensitic stainless steel CA6NM parts and homogeneously welded with filler metal 410NiMo. Results from recently concluded studies are gathered, thus establishing the state-of-the-art of the fatigue and fracture mechanics assessments of runners. Specifically, notions of fatigue in runners, the metallurgy of runner welds and fracture mechanics considerations applied to runner welds are presented. A case study is then shown in order to properly evaluate the impact of recently obtained results on the fatigue and fracture mechanics assessment of runners.
2. Fatigue in hydraulic turbine runners

2.1 A brief background on runner fatigue loading

As figure 1 shows, hydraulic turbine runners are subjected to numerous extrinsic solicitations, several of which are dynamic in nature. On one hand, the turbine’s operation scheme causes variations of static and transient operation loads, mainly through start-stop sequences, load rejection and runaway events as well as power variations (1). The load cycles thus incurred can be considered as low-frequency high-intensity (LFHI) fatigue cycles, i.e. they are associated with large stress variations occurring at very low frequencies (~10^-8 to 10^-4 Hz).

On the other hand, dynamic loads are associated with small stress fluctuations occurring at high frequencies typically a function of the runner’s rotational speed and the runner-distributor configuration. Rotor-stator interactions (2,3), vortex rope pulsations (4), inter-blade (5) and Von Karman vortices (6) are examples of phenomena that induce dynamic stresses in runners. In the event of a correspondence between the runner’s natural frequencies and exciting frequencies related to these phenomena, mechanical resonance can amplify these stress fluctuations, potentially leading to a high fatigue damage rate and significant crack propagation (7). The load cycles induced by dynamic loads can thus be considered as high-frequency low-intensity (HFLI) fatigue cycles, i.e. they are associated with small stress variations that occur at high frequencies (~10-200 Hz).

Figure 2 shows a schematized illustration of the evolution of stresses during a start-stop sequence ending with a load rejection reaching a temporary runaway. This case would be typical of a highly stressed location in a Francis runner where stresses are reversed upon synchronization and load rejection. The curve in red represents a case where tensile residual stresses are superposed to the load-induced stresses. In this case, it can be seen that the entire stress variation between nominal power and runaway composes the LFHI cycle, whereas if there is no residual stress, only the tensile portion of the stress variation contributes to fatigue damage. This illustrates the great influence that residual stresses can have on the effective fatigue cycles acting on the runner, which justifies the use of efficient post-weld heat treatments to maximally reduce detrimental tensile residual stresses.

Fatigue assessments of hydraulic turbine runners are based on the premise that LFHI cycles can trigger HFLI to contribute to fatigue damage (8), which should be avoided at all cost. Indeed, LFHI cycles can lead to some tolerated crack propagation, since they are associated with large stress variations. However, because of their very low frequencies, the total crack propagation over a given service life is minimal with an appropriate design. This is the basis of a damage tolerance design approach. On the other hand, HFLI cycles do not contribute to fatigue damage during service life as the low induced stress fluctuations are insufficient to promote crack propagation. However, as cracks propagate because of LFHI cycles, the near-crack tip stress field induced by HFLI fatigue surpasses the fatigue crack propagation threshold as fracture mechanics metrics are dependent on crack length. This event usually results in very fast crack propagation and imminent failure. Runners should therefore be designed to avoid this occurrence.

2.2 Metallurgical features of runner welds

Experience has shown that fatigue cracks in hydraulic turbine runners often initiate in the vicinity of welds and sometimes in the heat affected zone (HAZ) (7,9). Welds are complex systems from a metallurgical point of view. Martensitic stainless steel CA6NM homogeneous welds present even higher complexity mainly attributed to the formation of several phases and their low transformation temperature. CA6NM, on its own, has a triplex microstructure consisting of martensite as the primary phase and up to 5 %vol. and 30 %vol. respectively of δ-ferrite formed at high temperature and austenite retained from casting solidification and reformed during subsequent tempering treatments (10). Carbides can also precipitate at grain boundaries during heat treatments and deteriorate the fracture toughness (11), though this can be avoided with appropriate control of the elaboration process and the quantity of alloying elements (12). The filler metal (FM) typically used to homogeneously
Figure 2 Schematic representations of the stress variations incurred by LFHI fatigue cycles and HFLI fatigue cycles during a start-up sequence ending with a load rejection reaching runaway. Case where tensile residual stresses are superposed to the load-induced stresses is shown in red.

weld CA6NM, 410NiMo, contains the same phases but with significantly different morphologies. Oxide inclusions are also typically present in solidified 410NiMo to which its significantly reduced fracture toughness, when compared to base metal (BM) CA6NM, has been attributed (13).

Upon welding, a third region of interest in CA6NM and 410NiMo runner welds forms which is called the heat affected-zone (HAZ). The HAZ is defined as the zone in which solid-state phase transformations occur as a consequence of the high heat input during welding and subsequent cooling. In the case of CA6NM, the HAZ can be divided in several sub-regions depending on the maximum temperature reached and, hence, the local thermal cycles that induce phase transformations of different extents (10). Figure 3b shows optical micrographs of the microstructure in each of the weld regions of interest, e.g. the filler metal, the HAZ and the base metal.

2.3 Fracture mechanics considerations

2.3.1 A brief theoretical background

Fracture mechanics give the mathematical tools to properly assess the stresses in the vicinity of very sharp notches, i.e. cracks. It allows quantifying the near-crack tip stress field and properly assessing the crack tip singularity using the stress intensity factor $K$. The general relation that characterizes the stress field in the vicinity of cracks, when neglecting higher order terms, is given by:
where, $K_{I,II,III}$ is the stress intensity factor under fracture mode I (tension), II (in-plane shear) or III (out-of-plane shear) and $\sigma_{ij}^{I,II,III}$ is the corresponding stress field expressed in a polar coordinate system originating at crack tip. The stress intensity factor is usually expressed as a function of the far-field stresses using the following general equation:

$$K = Y \sigma_{\infty} \sqrt{\pi a}$$

where $Y$ is a function that mainly depends on the crack geometry and load configuration, $\sigma_{\infty}$ is the far-field stress and $a$ is the crack length. For simple geometries, analytical expressions of the stress intensity factor exist, whereas international standards suggest empirical relations calibrated by finite element analysis for more complex geometries that are easily defined by geometric parameters. For very complex geometries and load configurations, computational fracture mechanics methods can be used to obtain the stress intensity factor. The displacement correlation method (14) is probably the most widely used and well integrated technique in commercial finite element codes. This method allows obtaining the stress intensity factors from the calculated relative displacements of nodes surrounding the crack tip according to the following equations for a 2D case ($K_I$ and $K_{II}$):

$$K_I = (v_{i+1}-v_i) \frac{E \sqrt{2\pi/r}}{8(1-\nu^2)}$$

$$K_{II} = (u_{i+1}-u_i) \frac{E \sqrt{2\pi/r}}{8(1-\nu^2)}$$

Where $u_i,v_i$ and $u_{i+1},v_{i+1}$ respectively represent the displacements calculated at nodes $i$ and $i+1$ oppositely located on the crack surfaces at a distance $r$ from the crack tip.

Another aspect regarding the fracture mechanics characterization of a crack is to properly predict its propagation path when subjected to mixed-mode loading. In the context of runner fatigue assessments, this is vital in order to have a good knowledge of the stress intensity factor evolution against crack length, and hence, to correctly predict the crack propagation extent over the expected service life. Several criteria exist for the prediction of crack path direction, one of which states that a crack subjected to mixed-mode loading will propagate along the plane of maximum tangential stress (15). The crack kink angle $\theta$ when subjected to mixed-mode loading is then deducted from the following equation (2D case):

$$\theta = 2 \cdot \tan^{-1} \left( \frac{1}{4} K_I \pm \frac{1}{4} \sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8} \right)$$

Fatigue assessments in the case where defects are present, can be based on fracture mechanics metrics. It was shown by Paris et al. that the fatigue crack propagation rate $da/dN$ is well correlated with the stress intensity factor range $\Delta K = K_{max} - K_{min}$ incurred by the cyclic load (16). This led to the establishment of the widely known Paris relation, which is defined as:
\[
\frac{da}{dN} = C(\Delta K)^m
\]  

(5)

Where \( \frac{da}{dN} \) is the fatigue crack propagation rate (FCPR) in mm/cycle and where \( C \) and \( m \) are experimentally determined fitting parameters. By knowing the stress intensity factor range for a given crack length, the extent of crack propagation over a given number of cycles can therefore be well predicted using eq. 5.

2.3.2 Fatigue crack propagation behavior of runner weld materials

Recent studies from a large research consortium in Montreal developed extensive knowledge regarding the aqueous fatigue crack propagation behaviour of runner martensitic stainless steel homogeneous welds, especially in the HAZ (17–19). The main goal of these studies was to determine if the HAZ represented a weak link in terms of fatigue crack propagation in runners welded by flux-cored arc welding process. This was first assessed by comparing experimental fatigue FCPR measured in this zone with those measured in the unaffected base metal and filler metal 410NiMo. Crack propagation tests at constant stress intensity factor range on as-welded specimens revealed that the HAZ presented only slightly higher FCPR than the base metal, while the highest FCPR were measured in the filler metal. This was explained by the influence of the martensitic microstructure on the crack path, where fatigue cracks were found to follow the orientation of martensite laths. The martensite’s coarseness can therefore lead to more or less tortuous crack paths. A very tortuous crack path caused by a coarse martensitic microstructure is desirable because it leads to toughening by local mixed-modes of crack advance and roughness-induced crack closure (17). As was explained and modelled based on physical observations of crack paths in the three regions of the weld, the base metal possesses the highest resistance to fatigue crack propagation due to its coarse martensitic microstructure which led to a very tortuous crack path. The filler metal, on the opposite, typically presents a fine microstructure, which could have explained the highest growth rates measured in this zone. The HAZ was found to be a transition region, where an increasingly coarse microstructure from filler metal to base metal was associated with decreasing FCPR. Figure 3 shows comparative optical micrographs in each of the weld’s region of the resulting crack path and associated microstructure.

![Figure 3 Optical micrographs of (a) crack path and (b) microstructure in filler metal, heat affected zone and base metal.](image-url)
The crack path was schematically reproduced on the microstructure micrographs to better appreciate the relation between crack path tortuosity and microstructure coarseness.

These conclusions about the influence of the HAZ’s microstructure were further validated through the completion of standard fatigue crack propagation tests in an aqueous environment with the crack confined to the HAZ using special compact tension specimens (19). Figure 4 shows the tests results that were obtained at load ratios $R = K_{	ext{min}}/K_{	ext{max}}$ of 0.1 and 0.7 and on as-welded (AW) and heat treated (HT) specimens. The fatigue crack propagation curves of the base metal (BM) are also shown for comparison. The previously identified microstructural effects resulted in a somewhat lower crack propagation threshold at a load ratio $R = 0.1$ for the heat-treated HAZ, when compared to the base metal. This was rationalized by a lower extent of roughness-induced closure as a consequence of the finer microstructure in line with previous arguments. At $R = 0.7$, whether in the as-welded or heat-treated state, the fatigue crack propagation behaviour of the HAZ was very similar to that of the base metal. This was explained by the fact that the previously identified microstructural effects have less influence when the crack is fully open, e.g. at high load ratios or when tensile residual stresses are present at crack tip. As for the as-welded HAZ tested at $R = 0.1$, it was found that tensile residual stresses lead to an effective high load ratio behavior because they inhibited beneficial crack closure mechanisms. It was also determined that residual stresses have a greater influence than microstructure when it comes to the fatigue crack propagation of homogeneous martensitic stainless steel runner welds. The results also showed that typically conducted post-weld heat treatments are very efficient at relieving detrimental tensile residual stresses and thus reducing crack propagation rates. Furthermore, these studies showed that when a crack initiated and initially grew in the HAZ near the fusion line, it
had a tendency to gradually deviate towards the base metal. This was rationalized with the weld strength mismatch effect, where a gradient of yield strengths between the filler metal, HAZ and base metal, led to the formation of an asymmetric crack tip plastic zone. Knowing that fatigue crack-tip damage processes that lead to their propagation occur in this plastic zone and are promoted when it is larger, this resulted in the crack deviating to the side of highest yield extent, where the plastic zone was the largest, e.g. the base metal. This result shows that, although the HAZ was identified as having a somewhat lower intrinsic fatigue crack propagation resistance than the base metal, this zone does not represent a funnel for cracks. The crack propagation macroscopic trajectory is in fact mostly driven by its local crack tip stress field induced by the external loading.

3. **Case study: Critical defect assessment in a Francis runner**

This case study concerns the assessment of critical defect sizes near the toe of a rounded fillet weld in a Francis turbine runner (figure 5). This assessment method allows quantifying the size of defects that can be tolerated for a given life. In practice, surface indications are automatically repaired when detected using conventional non-destructive testing (NDT) techniques. Embedded flaws, however, are more difficult to detect and usual NDT techniques (i.e. ultrasonic and radiographic testing) can’t detect flaws smaller than a certain size. The calculation method used at Alstom allows confirming that defects that are identified as critical, e.g. defects that will propagate and lead to failure at the end of a given life, can be easily detected with usual NDT techniques.

![Figure 5 Schematized illustration of surface and embedded flaw near the weld toe at the trailing edge blade-band weld fillet in a Francis runner for critical defect assessment.](image-url)
Table 1 Calculated critical defect sizes in base metal and HAZ

|          | BM Width | BM Depth | HAZ Width | HAZ Depth |
|----------|----------|----------|-----------|-----------|
| Surface  | 3.86 mm  | 15.45 mm | 4.63 mm   | 18.50 mm  |
| Embedded | 3.31 mm  | 13.23 mm | 4.07 mm   | 16.26 mm  |

First the static stresses acting in the runner during normal operation and runaway were calculated by finite element analysis using the pressure field obtained from computational fluid dynamics calculations. Knowing the static stress at an area of interest, e.g. at the weld toe of the blade-band junction near the trailing edge for our case, cyclic stresses associated to representative cyclic loads blocks are determined. Considering the defects as cracks, the corresponding stress intensity factor ranges are calculated based on solutions proposed by British standard BS7910 at points A and B (figure 5). The extent of crack propagation, \( d_a \) and \( d_c \), is then calculated using the Paris law (eq. 5) for a flaw growing in the base metal and a flaw growing in the HAZ. Critical defect sizes corresponding to initial defects leading to failure at exactly a given lifetime are then recursively determined.

Table 1 shows the calculated surface and embedded critical defects. The results are presented for assumed elliptical shaped defects with a representative major to minor axis ratio of four. These results give a general appreciation of the degree of sensitivity of the Paris law material constants in fatigue crack propagation calculation methods in runners. It can be seen that the critical defects calculated in the HAZ are somewhat smaller than the ones calculated in the base metal but can still be easily detected using conventional NDT techniques. This is in line with the slightly lower resistance to fatigue crack propagation of this zone when compared with the base metal. However, it must be noted that for the HAZ case, the flaw was considered to be confined to this zone, which is a hypothetical worst-case scenario. In a real situation, significant crack deviation would most probably occur and the crack would grow in the HAZ for only a fraction of its propagation length. In deed, historical fatigue cracking occurrences in Francis runners have shown that though cracks are prone to initiate in the HAZ, this zone does not necessarily result in a preferential crack propagation path confined to it (7). Also, as previously mentioned, it was experimentally shown in (19) that the degree of yield strength mismatch in CA6NM and 410NiMo welds resulted in fatigue cracks gradually deviating towards the base metal, though considerable effort was put into the specimen’s and bench test design to force the crack to propagate solely in the HAZ. All these results allow reaching the conclusion that the HAZ does not represent a preferential channel for fatigue cracks to propagate in and does not compromise the fatigue crack propagation resistance of welded hydraulic turbine runners. Additional efforts should be put forth to determine if such a conclusion can also be obtained for filler metal 410NiMo, in which fatigue cracks can also propagate.

4. Conclusion
This study presented an overview of fatigue and fracture mechanics aspects in the welds of hydraulic turbine runners. Recent results regarding the fatigue crack propagation behaviour of welds and, more specifically, in HAZ were presented along with a case study. All these results show that the HAZ, though slightly less resistant to fatigue crack propagation than its base metal counterpart, does not represent a preferential region for crack propagation and, hence, does not deteriorate the runner’s fatigue resistance.

The field of hydraulic turbine runner fatigue represents a continuous source of research and development. Additional work should focus on, but not be limited to, the study of the influence of residual stresses on the fatigue crack propagation behaviour, the elaboration of more resistant microstructures and the improvement of numerical methods, notably regarding 3D crack propagation simulations. Innovations in these aspects will contribute to the end of fatigue cracking in hydraulic turbine runners.
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