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Microstructural effects on the fatigue crack growth resistance of a stainless steel CA6NM weld

Alexandre Trudel [a,b], Martin Lévesque [b], Myriam Brochu [b,*]

[a] *Global Technology Center in Sustainable Hydro, ALSTOM Hydro Canada Inc., Sorel-Tracy, Canada*
[b] *Department of Mechanical Engineering, École Polytechnique de Montréal, Montreal, Canada*

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The fatigue crack growth behavior of a martensitic stainless steel CA6NM hydraulic turbine runner weld was investigated to unveil microstructural effects in the filler metal, heat affected zone and base metal. Knowledge of such effects is paramount for engineers who design these components for long fatigue lifetimes. Constant stress intensity factor fatigue tests in river water environment revealed crack growth rate variations between the three weld zones. Tensile residual stresses were identified as a crack opening mechanism. Crack deflection concepts were used to relate the fatigue crack growth resistance to the weld microstructure. The conclusion of this study is that the crack growth path is largely driven by the weld's microstructural features, influencing the materials resistance to fatigue crack growth.

1. Introduction

1.1. Context of research

Martensitic stainless steel alloy CA6NM has been extensively used in the field of hydroelectricity for the manufacturing of critical components such as turbine runners. These components are usually assembled by welding cast blades to a cast core, in the case of propeller runners, and to cast band and crown in the case of Francis runners. Engineers design these components against fatigue with fracture mechanics concepts to account for casting and welding defects, as well as geometric discontinuities. Typically, allowable defect sizes are determined with fatigue crack growth laws to achieve a given service life. Similarly, the same fatigue and fracture criteria are used to establish optimal welded joints dimensions and to minimize required filler metal quantity. Therefore, extensive knowledge of the fatigue crack growth behavior of materials used, as well as of potential microstructural effects, is required.

The microstructural characteristics of CA6NM welds result from the combined actions of the casting process, heat treatments and welding process. Typically, CA6NM has a tempered martensitic microstructure and can contain ferrite and austenite in proportions of up to 5 vol.% and 30 vol.%, respectively [1].

The fatigue crack growth behavior can be affected by microstructural characteristic features, such as grain size. In the case of martensitic steels, the martensite morphology can also play a role when the fatigue crack follows martensite laths favorably oriented inside packets that form within prior austenite grains [2]. The tortuosity extent of the crack path can

* Corresponding author. Address: École Polytechnique de Montréal, 2500 chemin de Polytechnique, Montréal, Québec H3T 1J4, Canada.
E-mail address: myriam.brochu@polymtl.ca (M. Brochu).

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Nomenclature

B	Compact tension specimen thickness
$(da/dN)_D$	Effective fatigue crack growth rate of a crack with deflections
$(da/dN)_D$	Fatigue crack growth rate of a crack with no deflections
D	Length of deflected crack segment
K_{cl}	Stress intensity factor at closure
K_{max}	Maximum stress intensity factor
ΔK	Stress intensity factor range
$r_{y,c}$	Plane strain cyclic plastic zone size
$r_{y,m}$	Plane strain monotonic plastic zone size
R	Load ratio
S	Length of linear crack segment
$\sigma_{res,z}$	Residual stress perpendicular to nominal crack growth plane
σ_y	Yield strength
θ	Angle of crack deflection
W	Compact tension specimen width

Acronyms

BM	Base metal
CT	Compact Tension
COD	Crack opening displacement
EDM	Electrical discharge machining
FCAW	Flux-cord arc welding
FCGR	Fatigue crack growth rate
FEA	Finite element analysis
FL	Fusion line
FM	Filler metal
HAZ	Heat affected zone
PAG	Prior austenite grain
SEM	Scanning electron microscope
TRIP	Transformation-induced plasticity
XRD	X-ray diffraction

be influenced by such features, as shown by many experimental results, where coarse microstructures, e.g. large grains, led to abrupt deflections and a tortuous crack path [3–5]. A tortuous crack path is known to improve fatigue crack growth resistance by promoting roughness-induced crack closure and by reducing the effective crack tip driving force due to local mixed modes of crack advance [5–7]. These extrinsic toughening mechanisms are more significant in the near-threshold regime, when compared to the Paris regime [8]. This stems from two phenomena: (1) for low stress intensity factor ranges, the crack path is strongly influenced by crystallographic orientation because of the small plastic zone size, and (2) the crack tip opening displacements are of similar size than the asperities created by crack deflections. In the Paris regime, cyclic crack extensions span over several characteristic microstructural features lengths and crack tip opening displacements are larger, resulting in a reduced influence of the microstructure and closure on the resistance to crack growth.

The austenite phase in alloy CA6NM is retained from the quenching operation and/or reversed from the tempering treatment [9]. In the welding heat affected zone, additional austenite can stabilize after cooling in the area where martensite partially transforms to austenite upon heating [1]. Given sufficient strain energy, e.g. in the plastic zone of a fatigue crack, austenite can transform to martensite. This strain-induced transformation is accompanied by a volumetric expansion that can lead to the establishment of local residual stresses when constrained by surrounding elastic material. This is known as transformation-induced plasticity (TRIP effect). The TRIP effect was proven to be beneficial to the fatigue crack growth resistance of steels containing austenite as a primary phase, such as austenitic stainless steels [10–12]. The beneficial effect of retained austenite as a secondary phase within high strength martensitic steels has also been recognized, where steels containing retained austenite were found to have an improved resistance to fatigue crack growth [13,14]. The TRIP effect is known to have more influence for higher stress intensity factor ranges, where large plastic strains in the crack tip plastic zone promote the austenite–martensite transformation [15]. In the near-threshold regime, low stress intensity factors can result in insufficient strain energy to trigger the transformation. The transformation of retained austenite during fatigue crack growth was observed in CA6NM for stress intensity factor ranges in the Paris regime [16], but its effect on the resistance to fatigue crack growth requires more attention.