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Characterizing the effect of residual stresses on high cycle fatigue (HCF) with induction heating treated stainless steel specimens

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ABSTRACT

A new method for introducing a predetermined amount of residual stresses in stainless steel thick-walled hollow fatigue test specimens was developed by the authors [1] using high frequency induction heating. The advantage of the proposed method over more traditional approaches is to avoid any change in other important fatigue parameters, i.e. surface roughness, geometry, and microstructure, while introducing the residual stresses. The last point only holds if the material under study does not undergo any phase transformation within the range of temperatures and time exposures reached during the heat treatment. In this paper, the effect of residual stresses on high cycle fatigue (HCF) life of annealed AISI 304L stainless steel is investigated by introducing a residual stress field in thick-walled hollow fatigue specimens and by comparing the fatigue life obtained with the reference *S–N* curve. For the particular case studied, a surprising observation is made. Introducing tensile residual stresses beneath the surface of hollow fatigue specimens using the method proposed by Paquet et al. [1] leads to improved HCF lives. Validity of this result is confirmed by a statistical analysis. Residual stresses were analyzed by the X-ray diffraction (XRD) technique to rationalize this experimental result. The increase in fatigue life is explained by residual stresses evolution within the specimen cross section during the fatigue test, leading to a build up of compressive residual stresses beneath its surface. This is a clear demonstration that assimilating residual stresses resulting from fabrication processes to superimposed static mean stresses can lead to considerable errors in fatigue life predictions.

1. Introduction

Over the past decades, fatigue cracking of turbine runners has been identified as one of the major causes for forced shutdowns in hydroelectric industry. Consequently, prediction and improvement of their useful life has become a key issue for lowering the costs associated with their repair or replacement. Reliability of turbine runners depends primarily on the design, on the quality of the welds and on the operating conditions. Applied stresses consist of external loads as well as internal residual stresses (RS), which are introduced prior to their use during fabrication or after a repair. Though it is widely accepted that RS is a fatigue limiting factor, design often employs empirical methods rather than rigorous numerical methods to account for their influence. Quantifying the effect of RS on fatigue is not straightforward because their effect cannot be easily isolated from those of other parameters such as the applied loads, the surface roughness, the geometry, and the microstructure. In this paper, a novel experimental method is used to study the sole influence of RS on fatigue strength. This is achieved by introducing a predetermined RS field in thick-walled hollow fatigue test specimens using high frequency induction heating, and by comparing their fatigue life with the reference material *S–N* curve.

High frequency induction heating was shown to be an effective way to introduce RS in thick-walled hollow fatigue test specimens without affecting their surface roughness, their geometry, nor their microstructure [1]. Microstructural effects are avoided by using AISI 304L stainless steel that remains austenitic for temperatures below 1000 °C. The heating parameters (duration, power, frequency, etc.) required to obtain a desired RS field are determined using the finite element method (FEM). Circulation of water in a hole drilled along the axis of the specimens avoids an excessive heating of their core and increases the intensity of induced RS [1]. Other methods have been used to introduce RS in laboratory specimens such as welding [2–5], surface treatments [6–8], heat treating [9,10] and the application of local plastic strains, e.g. through strain-hardening of a notch tip [11] or application of a proof stress [12], that introduce a RS field after unloading. None of these methods is successful in introducing RS in laboratory

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Nomenclature

FEM	Finite element method
HCF	High cycle fatigue
LCF	Low cycle fatigue
LVDT	Linear variable differential transformer
RS	Residual stress(es)
XRD	X-ray diffraction
α,β	Parameters of Dang Van multiaxial fatigue criterion
δ	Induction heating penetration depth
μ	Average of a statistical variable
μ_{em}	Magnetic permeability
ϕ	Diameter
$\boldsymbol{\sigma}$	Stress tensor
σ^2	Variance of a statistical variable
σ_H	Hydrostatic stress
$\boldsymbol{\sigma}^R$	Residual stress tensor
$\boldsymbol{\sigma}^S$	Service stress tensor
σ_{em}	Electric conductivity
σ_y	True yield strength
$\boldsymbol{\tau}$	Mesoscopic shear stress vector
A,B	Interpolation coefficients
E	Young's modulus
F(N)	Cumulative probability for the number of cycles to fracture N
N	Number of cycles at final fracture
N_1	Shortest fatigue life at a given stress amplitude S_a
P	Probability
R	Stress ratio $R = \frac{S_{min}}{S_{max}}$
S_Y	Engineering yield strength
S'_Y	Engineering cyclic yield strength
S_a	Prescribed stress amplitude
S_a^D	Fatigue strength at 1×10^7 cycles in fully reversed fatigue
S_m	Prescribed static mean stress
S_{max}	Maximum prescribed stress
S_{min}	Minimum prescribed stress
T	Time period
X,Y	Interpolation variables
d	Depth
f	Frequency
f(N)	Probability function for the number of cycles to fracture N
n	Unit vector
t	Time

specimens without affecting their surface roughness, their geometry or their microstructure. Hence the need for the method developed in [1].

In this paper, RS are introduced in annealed AISI 304L stainless steel thick-walled hollow fatigue test specimens by means of high frequency induction heating and their influence on high cycle fatigue (HCF) life is investigated. The experimental results show that introducing tensile RS beneath the surface of the hollow specimens may increase their fatigue life because of their relaxation and stabilization as compressive ones. Residual stresses are analyzed by X-ray diffraction (XRD) and the increase in fatigue strength of specimens is related to RS evolution during the fatigue tests. This indicates that assimilating fabrication/repair RS to a static mean stress for design may lead to significant errors in fatigue life predictions and that the stabilized residual stress field, after relaxation if any, should instead be considered in the fatigue analysis as pointed out in [13–16,9] among others.

The structure of the paper is as follows. The experimental method is first described in Section 2. Fatigue tests results are then reported in Section 3 and their statistical validity assessed. A thorough discussion follows in Section 4 and a conclusion is finally drawn in Section 5.

2. Experimental method

The experimental method used to introduce RS in fatigue test specimens and the HCF tests undertaken to study their influence on fatigue life of AISI 304L stainless steel are briefly discussed next.

2.1. Residual stress conditioning

Induction heating is widely used for surface treatments. While a low frequency results in uniform heating, high frequency allows concentrating the heating power in a thin surface layer and hence, generates high temperature gradients within the specimen or component. In addition to the heating frequency f, the penetration depth δ depends on the electromagnetic properties of the specimen. It is expressed as follows [17]:

$$\delta = \sqrt{\frac{1}{\pi f \sigma_{em} \mu_{em}}} \tag{1}$$

where μ_{em} and σ_{em} are the material magnetic permeability and electric conductivity respectively.

The temperature gradient resulting from high frequency induction heating was used in [1] to introduce tensile RS beneath the surface of thick-walled hollow fatigue test specimens. For the specific case of AISI 304L stainless steel ($\mu_{em} = 4\pi \times 10^{-7}$ N/A^2, $\sigma_{em} = 1.38 \times 10^6\ \Omega^{-1}\ \text{m}^{-1}$), a penetration depth $\delta = 0.71$ mm was obtained with a 360 kHz induction heating set-up. This heating device is equipped with a heating coil (nominal diameter 28.5 mm) composed of 4.5 turns of copper wire. The maximal power that can be delivered by the system is 30 kW. A full description of the set-up can be found in [1].

Induction heating parameters used to introduce RS in the fatigue specimens were optimized in order to generate an RS field with desired intensity [1]. The optimization process had to take into account the following constraints:

(1) The temperature gradient induced along the radial direction of the specimen needs to be large enough to induce sufficient plastic deformations for generating high intensity RS field upon cooling.
(2) The temperature reached at the center of the sample should be low enough to avoid creep and softening effects that would significantly reduce the induced RS field intensity.

The second constraint forced the development of a new design for the fatigue specimens, characterized by a inner hole used to circulate cooling water. The geometry of this specimen is shown in Fig. 1.

The RS field introduced by 1.4 s of heating at maximum power (30 kW) was assessed with an in-house multi-physics finite element method (FEM) code and the computed RS field validated with X-ray diffraction (XRD) [1]. A very good match was found between the experimental measurements and the simulation results. A contour plot showing the distribution of longitudinal (or axial) residual stress σ_{yy}^R in the fatigue specimen is given in Fig. 2a, while