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Understanding of fatigue crack growth behavior in welded joint of a new generation Ni-Cr-Mo-V high strength steel

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ABSTRACT

This study was mainly concerned with the long fatigue crack growth rate (FCGR) of a new generation Ni-Cr-Mo-V high strength steel and its welded joints used in modern marine environment. Several major factors, including stress ratio, microstructure, welding residual stresses (WRSs) and specimen thickness were investigated. Results showed that the weld metal (WM) possessed better resistance to crack propagation relative to the base material (BM) under each stress ratio owing to the interlocking acicular ferrite microstructure and the resultant higher crack closure level. WRSs partly retained in the extracted fracture mechanics samples and noticeably affected FCGR of the WM. Post-welding heat treatment could never eliminate the WRSs and might generate new residual stress distribution. Both the crack closure model and the two-parameter model yielded fairly good consolidation for the *R*-ratio effect of the BM whereas they failed to correlate the data for the WM because of the retained WRSs. Accelerated FCGR with increased specimen thickness was measured for both the BM and the WM. The fracture mechanism was scrutinized by means of fractography and fatigue trajectory map. The results obtained in the present work are helpful in shedding light on the damage tolerance design of the Ni-Cr-Mo-V high strength steel welded joints employed in modern marine structures.

1. Introduction

High strength steels are playing increasing roles in the design of modern shipbuilding and marine structures. The demand for high load carrying capacity of these structures has put forward to the use of high strength steels with martensite type microstructure, which is generally understood as possessing the best tensile properties. However, martensite also has poor toughness due to its brittleness. Welding has been applied as a commonly used technique in the connection of high strength steels. It has been known that the tendency of cold cracking gets higher in the welded joint when strength of the steel increases. On the other hand, the unavoidable welding defects which serve as potential crack initiation sites give rise to the occurrence of fatigue failure.

It is generally accepted that the mechanical properties of the weld metal, from both a strength and toughness point of view, are very much dependent on its microstructure feature. Acicular ferrite, first described in the early 1970s, was regarded as the optimum microstructure due mainly to its nature of small grain size and high angle boundaries [1]. It was purposefully introduced into the welding of "hard and brittle" high strength steels to improve the toughness of their joints.

The welded structures of marine application are often exposed to complex cyclic wave loadings and fatigue failure has been a major cause of failure. As argued by numerous researchers, e.g. Hobbacher [2], due to the inherent weld imperfections that can serve as initial cracks, fatigue life of welded joints can be treated largely as crack propagation life. Damage tolerance design based on

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Nomenclature

a	crack length of CT specimen
a_0, a_1, a_2	material constants in the proposed two-parameter model
C, m	coefficient and exponent of Paris-Erdogan laws
da/dN	fatigue crack growth rate (cyclic loading)
E	Young's modulus
K	stress intensity factor
K_c	geometry dependent fracture toughness
K_{max}	maximum K in a loading cycle
K_{op}	crack opening stress intensity factor
N	number of loading cycles
P_{max}	maximum applied force
P_{min}	minimum applied force
P_{op}	crack opening force
R	stress ratio in cyclic loading
U	crack closure parameter
α	normalized sensitivity exponent in Walker's two-parameter model
ΔK	stress intensity factor range
ΔK^+	positive part of stress intensity factor range
ΔK_{appl}	applied stress intensity factor range
ΔK_{eff}	effective stress intensity factor range
ΔP	applied force range
$\Delta \varepsilon$	strain increment
σ	stress (general)
σ_{max}	maximum stress in a loading cycle
$\sigma_{ys0.2}$	0.2% proof yield strength
σ_{UTS}	ultimate tensile strength

Acronyms

BM	base material
COD	crack opening displacement
CT	compact tension
CTS	compact tension shear
FCGR	fatigue crack growth rate
GMAW	gas metal arc welding
PICC	plasticity induced crack closure
PWHT	post-welding heat treatment
SEM	scanning electron microscopy
SIF	stress intensity factor
WM	weld metal
WRS	welding residual stress

fracture mechanics concepts is needed under this circumstance [3]. Since fatigue crack growth (FCG) data are critical inputs for damage tolerant design, it should be extensively investigated to ensure the safety of marine structures. The relation between fatigue crack growth rate (FCGR) and the stress intensity factor (SIF) range was first detected by Paris and Erdogan [4]. They found that when plotting the FCGR data against the nominal SIFs on a double logarithmic scale, a fairly good linear relation was achieved. So the well known Paris-Erdogan law was proposed which was an empirical power law based on test data:

$$da/dN = C(\Delta K)^m \tag{1}$$

where coefficients C and m are material constants. da/dN is the crack growth rate and ΔK is the stress intensity factor range.

Several factors affect the FCGR of a material. The most significant one may be the stress ratio-R. Although an apparently anomalous behavior in that there was very weak R-ratio dependency in the Paris regime was reported for some steels by Jones et al. [5], the effect of R-ratio on FCGR has been extensively investigated as a common phenomenon for many materials during the past few years. Conventional representation of crack growth rates as a function of a single driving force as depicted by Eq. (1) is considered as inadequate to correlate the R-ratio effect. In general, two methods are often used, namely the two-parameter method and the crack closure method, to attain an effective crack driving force that can correlate the R-ratio effect with some physical basis.

(1) The two-parameter model (also referred as the superposition method or the effective stress ratio method in some studies)

The two-parameter model is generally considered to be based on the Smith-Watson-Topper fatigue damage parameter [6], which believes that it is the product of the maximum stress σ_{max} and half of the strain range $\Delta\varepsilon/2$ ahead of the crack tip that controls the damage process of fatigue. Because there are only two independent variables between the stress intensity factor range ΔK, the maximum stress intensity factor K_{max} and stress ratio R, any two of them was able to represent the whole information of a cyclic loading. The R-ratio effect on FCGR was first discussed by Walker [7]. Based on experimental data, Walker pointed out that the FCG driving force is controlled by a combination of R and ΔK, which is called the two-parameter driving force. Kujawski extended Walker's model to correlate FCG data for $R < 0$ by replacing the driving force with a new one - $(K_{max}\Delta K^+)^{0.5}$ [8] and further, $K_{max}^{\alpha}(\Delta K^+)^{1\text{-}\alpha}$ [9]. Nooriz et al. [10] also derived an analogous two-parameter model based on the elastic–plastic crack tip stress–-strain field analysis in the material volume adjacent to the crack tip. Other two-parameter models include those proposed by Huang and Moan [11], Li et al. [12] and Zhan et al. [13]. Sadananda and Vasudevan [14] insisted that an unambiguous description of fatigue crack growth requires two loading parameters: ΔK and K_{max}. They also pointed out that by introducing the two-parameter method, many effects, including the R-ratio, can be explained without invoking any extraneous factors, such as crack closure concept. Generally, it can be summarized that the FCGR equation in the intermediate regime can be characterized by a unified form: $da/dN = C(\Delta K{\cdot}f(R))^m$. This means that the crack growth driving force can be represented by the multiplication of ΔK and a function of the stress ratio, $f(R)$.

(2) The crack closure model (also called the effective stress intensity factor range method)

Another explanation for the so-called R-effects was provided by Elber [15] who introduced the concept of plasticity-induced crack