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Base material fatigue data for low alloy forged steels used in the subsea industry. Part 2: Effect of cathodic protection

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ABSTRACT

In air S–N fatigue data for forged low alloy steels as used in the subsea industry are presented in Part 1 of this paper. The test scope in Part 1 included testing to quantify the effect of the surface roughness, mean stress and material strength on the high cycle fatigue strength of low alloy steels with a tensile strength in the range of 600–800 MPa. A method for estimating the in air S–N curve from the tensile strength (material grade), surface roughness (machining) and mean stress (such as residual stresses, pressure testing, pre-load and external loads) is presented in Part 1. In this Part 2, fatigue test results for low alloy steels and one carbon steel tested in seawater with cathodic protection with a potential of −1050 mV versus an Ag/AgCl reference electrode are presented. The fatigue testing has been performed using smooth specimens. The tested smooth specimens have (actual) tensile strengths in the range from 627 to 790 MPa. Penalty factors for the tested smooth specimens in seawater with cathodic protection with respect to in air performance (Part 1) are presented and compared with penalty factors used in fatigue design codes such as DNVGL-RP-0005 (former DNV-RP-C203) and BS 7608. The obtained environmental reduction factors are found to be in accordance with the penalty factors used in BS 7608 provided that the maximum stress in the cycle is less than 94% of the yield stress for the material. The penalty factors used for forged steels in DNVGL-RP-0005 are non-conservative compared to the test outcome for the steel tested in an artificial 3.5% NaCl seawater solution. For higher stress levels, larger penalty factors than used in BS 7608 are required. It is found that the obtained S–N based environmental reduction factors are of similar magnitude as BS 7910 fatigue crack growth based reduction factors for CP.

1. Introduction

Cathodic protection (CP) systems are commonly used for corrosion protection of external surfaces of subsea equipment. For completion workover riser systems and wellhead systems sacrificial anodes are frequently used. Riser joints are typically protected by the use of a thermally sprayed aluminium metal coating on the outside.

Low alloy steels are considered to be cathodically protected if the potential is −800 mV or lower vs. Ag/AgCl reference electrode. Design guidance for cathodic protection systems of steels structures in marine environments is given in DNV-RP-B401 [1].

Failure of duplex stainless steel subsea components have been reported. The failures have occured due to hydrogen induced stress cracking (HISC), i.e., the combination of tensile stresses and local hydrogen embrittlement caused by adsorption of hydrogen formed at the steel surface due to the cathodic protection. These failures have resulted in the recommended practice DNV-RP-F112 [2] for the design of duplex stainless steel subsea equipment exposed to cathodic protection. DNV-RP-F112 [2] limits the membrane plus bending stress in smooth sections without stress raisers or welds to the minimum specified yield strength for the material. This RP [2] states that “duplex stainless steels are susceptible to HISC when exposed to elevated stresses in conjunction with cathodic protection potentials more negative than about −850 mV relative to a Ag/AgCl reference electrode”. A potential of −1050 mV Ag/AgCl as provided by Aluminium–Zinc based sacrificial anodes produce more hydrogen at the steel surface than −850 mV Ag/AgCl and is therefore considered to be more detrimental from a fatigue point of view [3,4]. CP is also found to reduce the failure strain for low alloy steels [5]. High strength steel is considered to be more vulnerable to hydrogen embrittlement than medium strength steel.

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Nomenclature

a	crack depth
c	half flaw length for a surface flaw
C	fatigue crack growth constant
CP	cathodic protection
ERF	environmental reduction factor
F	geometry factor
FCG	fatigue crack growth
HISC	hydrogen induced stress cracking
ID	internal pipe diameter
$\log a$	intercept constant for the S–N curve
$\log \bar{a}$	design intercept constant for the S–N curve
m	fatigue crack growth exponent or slope of the S–N curve
N	number of cycles to failure
N_{air}	number of cycles to failure in air
N_{CP}	number of cycles to failure in seawater with CP
OD	external pipe diameter
QT	quenched and tempered
R	stress ratio $= S_{min}/S_{max}$
R_a	arithmetic average surface roughness height
R_m	tensile strength at room temperature
$R_{p0.2}$	yield strength at room temperature
S_a	stress amplitude
S_m	mean stress
S_{max}	maximum stress in the cycle $= S_m + S_a$
S_{min}	minimum stress in the cycle $= S_m - S_a$
SMYS	specified minimum yield strength
Z	reduction of area at failure
ε_f	fracture strain
ΔK	stress intensity factor range
ΔK_{AB}	stress intensity factor range at the intersection between stage A and stage B
ΔS	stress range $= 2 \cdot S_a$

Present industry practice is to avoid environmental assisted cracking by selecting materials with limited hardness and yield strength [6]. For example, ISO 13628-7 [7] for completion and workover riser systems specifies a maximum Vicker's hardness HV10 of 350 for cathodically protected low alloy steels. With the use of the conversion equation from BS 7910 [8] this corresponds to a maximum allowable yield strength of 927 MPa and a maximum allowable tensile strength of 1147 MPa. ISO 13628-7 [7] defines accidental (single load event), extreme (short duration, say 30 days) and normal operating load conditions (design life of typically 15 years) and associated structural design factors [6]. The accidental single load capacity in ISO 13628-7 for pipes is set equal to the plastic limit load, that is, through thickness yielding for internal pressure and applied tension and the formation of a plastic hinge for bending [9,10,6]. The load is limited to 80% and to 67% of the accidental load capacity for extreme and normal operating load conditions, respectively.

Fatigue codes for offshore steel structures, such as DNVGL-RP-0005 [11] and BS 7608 [12], provide guidance for the fatigue analysis of steels in-air, in seawater with or without cathodic protection. However, none of these codes provide valid guidance for the use of high strength steels in ISO 13628-7 [7] and ISO 13628-4 [13] equipment that can be subjected to high cyclic stresses and at the same time are used in seawater with cathodic protection. DNVGL-RP-0005 is valid for steels with a (minimum specified) yield strength of less than 550 MPa in seawater with free corrosion and with CP. BS 7608 covers steels with yield strengths in the range from 200 to 960 MPa and ultimate tensile strengths in the range from 360 to 1200 MPa but limits the maximum fibre stress in the net area of the component, excluding peak and secondary stresses, to 60% of the yield stress for normal operating conditions and to 80% under extreme load conditions. BS 7608 also requires that the maximum number of cycles exceeding normal operating conditions in the design life should not exceed 100. Hence, these fatigue codes provide limited guidance for the safe usage of high strength steels in seawater with cathodic protection in combination with high allowable stresses for ISO 13628-7 [7] and ISO 13628-4 [13] subsea equipment. The HSE report [4] points out that very limited amount of fatigue data for forged high strength steels in seawater with CP exist. It is further recommended that more fatigue test data of candidate high strength steels in seawater with CP are needed.

This paper presents fatigue test results for low alloy steels tested in artificial seawater with cathodic protection with a potential of −1050 mV Ag/AgCl with (actual) tensile strengths in the range from 627 to 790 MPa. Test results for a QT (quenched and tempered) steel with a tensile strength of 627 MPa, AISI 8630 M steel with a tensile strength of 771 MPa and a API 5CT Grade T95 Type 1 (hereafter referred to as T95) steel with a tensile strength of 790 MPa are presented. The QT steel and the T95 carbon steel were tested in ASTM D1141 substitute ocean water while the AISI 8630 M steel was tested in a 3.5% NaCl seawater solution. The aim of the testing was to provide design guidance for use of these low alloy steels in combination with the high stress utilisation as allowed in ISO 13628-7 [7]. The tested materials are frequently used in the subsea industry. The reduction factors from the performed S–N testing in seawater with CP are compared with fracture mechanics based reduction factors as obtained using fatigue crack growth data from BS 7910 [8].

2. Design S–N curves for steels in seawater with CP

DNVGL-RP-0005 [11] and BS 7608 [12] are the two main fatigue design codes for offshore steel structures including subsea equipment. These two codes include S–N curves for non-welded and welded steels used in-air, in seawater with and without CP. Design S–N curves for non-welded steels from these two codes are presented below.

2.1. DNVGL-RP-0005

The B1 and the HS (high strength) class S–N curves are the two most commonly used S–N curves from DNVGL-RP-0005 [11] in fatigue analysis of machined low alloy steel forgings. Requirements and limitations for these two S–N curves are listed in Table 2. As can be seen from Table 2, DNVGL-RP-0005 only provides design fatigue data for steels in seawater having a yield strength less than 550 MPa. The HS curve for seawater with CP has a very limited application range as it only valid for steels having a yield strength in the range from 500 to 550 MPa.

The DNVGL-RP-0005 class B1 and HS S–N curves are compared in Fig. 2. The B1 curve for seawater with CP has been established from the in air B1 curve by dividing the fatigue life by a factor of 1.6 ($ERF = N_{air}/N_{CP}$) for stress ranges giving fatigue lives $< 10^6$ cycles. For longer fatigue lives, the penalty reduces until in-air performance is achieved for $\geqslant 10^7$ cycles.

The DNVGL-RP-0005 S–N curves for welds, bolts and threaded rods (studs) have been reduced by a factor of 2.5 for $N < 10^6$ cycles for seawater with CP and by a factor of 3.0 for $N < 10^7$ cycles for