INFLUENCE OF STEEL COMPOSITION ON THE MECHANICAL PROPERTIES AND Zn-Mg-Al COATING LAYER ON THE CORROSION RESISTANCE OF STEEL WIRE ROPES FOR OFFSHORE APPLICATIONS

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***Dedicated** to*

My chairman, My family, My Supervisor

&

Kiswire Top Management

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ABSTRACT

Steel rope is generally used for mooring application. Recently, higher strength and corrosion resistance are required to avoid the weight penalty with increase of the sea-water depth in offshore oil production. This can be achieved by increasing the carbon content and adding alloy elements in zinc coating. Three objectives of the research were conducted as follows; to investigate the effect of composition on strength and corrosion resistance of galvanized wire, to investigate the degradation mechanism of high tensile strength (2,150 ~2,250MPa) galvanized steel rope in sea-water and to develop a Zn-Al-Mg ternary alloy coating to enhance the corrosion resistance of steel ropes. Microstructural characterisation on coated steel wires was carried out using optical microscope, field emission scanning electron microscope (FESEM) equipped with energy dispersive spectrometer (EDS) and X-ray diffractometer (XRD). Both *Tafel* polarization and salt spray tests were conducted to investigate the corrosion resistance of Zn-Mg-Al alloy coatings. Torsion, fatigue and tensile tests were conducted. The best fatigue property was obtained at 2,167MPa tensile strength. Tensile strength above 2,167MPa, fatigue and torsion properties were reduced and the susceptibility to surface defect also was increased during fatigue testing, by which cracks can be easily created and grown at different planes at the same time. It is the main cause of fatigue degradation. Degradation of mooring rope is caused by combination of fretting and corrosion which normally occurs in wire rope assembly type known as Independent Wire Rope Core (IWRC). Excellent corrosion resistance over 3,000 hours based on salt spray test was obtained by addition of magnesium and aluminium elements in the range of 1.0~3.0wt% but no improvement for over 3wt% Mg, which might be attributed to coarsening of the phase grains. The multi-layer coatings in which each layer consists of several different alloy phases has an advantage because each phase has a unique function and they exert their synergic functions in corrosion environment. As a conclusion, applying Zn-Mg-Al coating to mooring rope improves life span of rope due to reduced crack in the coating and excellent corrosion resistance.

ABSTRAK

Tali keluli secara umumnya digunakan untuk aplikasi menambat. Mutakhir ini, kekuatan yang tinggi dan rintangan terhadap kakisan adalah diperlukan untuk mengelakkan penalti berat terhadap pertambahan kedalaman air laut pada penghasilan minyak di luar pesisir pantai. Ini dapat dicapai dengan meningkatkan kandungan karbon dan menambah unsur aloi dalam salutan zink. Tiga objektif kajian yang telah dilaksanakan adalah seperti berikut; mengkaji kesan komposisi terhadap kekuatan dan rintangan kakisan dawai tergalvani, mengkaji mekanisma degradasi kekuatan tegangan tinggi (2,150 ~ 2,250 MPa) tali keluli tergalvani di dalam air laut dan menghasilkan salutan aloi pertigaan Zn-Al-Mg untuk meningkatkan rintangan kakisan terhadap tali keluli. Pencirian mikrostruktur pada dawai keluli tersalut telah dilaksanakan dengan mengunakan mikroskop optik, mikroskop medan pancaran elektron imbasan (FESEM) yang dilengkapi dengan spektrometer serakan tenaga (EDS) serta pembelau sinar-X (XRD). Kedua-dua polarisasi *Tafel* dan ujian semburan air garam telah dijalankan untuk mengkaji sifat rintangan kakisan salutan aloi Zn-Mg-Al. Ujian kilasan dan tegangan telah dijalankan. Sifat kelesuan yang paling tinggi dicatat pada 2,167 MPa. Kekuatan tegangan melebihi 2,167 MPa, sifat kilasan dan lesu berkurang dan kerentanan terhadap kecacatan permukaan meningkat apabila ujian kelesuan, di mana retak mudah terbentuk dan pada masa yang sama merebak pada satah yang berbeza. Ini adalah faktor utama degradasi kelesuan. Degradasi tali penambat adalah disebabkan kombinasi diantara perlagaan antara dawai dan kakisan yang lazim berlaku pada jenis perhimpunan tali dawai dikenali sebagai *Independent Wire Rope Core* (IWRC). Rintangan kakisan yang terbaik dapat diperolehi pada jangka masa melebihi 3,000 jam berdasarkan kepada ujian semburan garam dengan penambahan unsur magnesium dan aluminium dalam lingkungan 1.0~3.0% berat namun tiada penambahbaikan selepas melebihi 3% berat Mg, mungkin disebabkan oleh pembesaran fasa bijian. Salutan pelbagai-lapisan yang mana setiap lapisan mengandungi beberapa fasa aloi berbeza mempunyai kelebihan kerana setiap fasa memiliki fungsi unik dan memberi fungsi sinergi di dalam persekitaran kakisan. Kesimpulannya, mengaplikasikan salutan Zn-Mg-Al kepada tali penambat dapat menambah baik jangka hayat tali disebabkan salutan mempunyai keretakan yang lebih rendah dan rintangan kakisan yang lebih tinggi.

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CPS	-	Counts per second
CR	-	Corrosion rate
DLP	-	Direct in line patenting
EG	-	Electro galvanized
EDX	-	Energy Dispersive X-Ray Spectroscopy analyzer
EIS	-	Impedance spectra test
FESEM	-	Field Emission Scanning Electron Microscope
FPSO	-	Floating production storage and offloading
HDG	-	Hot dip galvanizing
HDPE	-	High density polyethylene
ICP-MS	-	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	-	Inductively Coupled Plasma Emission Spectrometry
IWRC	-	Independent Wire Rope Core
LPD	-	Lead patenting process
mm	-	Millimeter
mm/y	-	Millimeter per year
N/mm^2	-	Newton per millimeter square
PVD	-	Physical vapour deposition
RC	-	Rope core (strand of IWRC)
SC	-	Core strand
SCE	-	Saturated calomel electrode
SPM	-	Single point moorings
T-T fatigue	-	Tension-tension fatigue
XRD	-	X-ray diffraction
α	-	Entrance angle

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

The global offshore oil industry is expected to continue to increase in the coming years, driven by the depleting onshore reserves and the discovery of new large offshore reserves. Oil production in deep and ultra-deep waters has significantly helped to advance new technologies. However, in exploring oil at depths beyond 1500 meters, steel wire ropes experience many challenges which stem from the sheer weight of the mooring system [1]. As water depth increases, conventional all-steel spread mooring systems show a number of limitations, both in operation and on the environment [2]. Such limitations include a lower restoring efficiency, high proportion of tether strength consumed by the vertical components of line tension, reduced pay-load of the vessel, and large mooring radius and sea-floor footprint [2]. The weight penalty of steel wire also increases rapidly with water depth and has become a significant cost driver for water depths beyond 2000 meters [3].

The obvious solution to these limitations is to avoid the weight penalty. There are two possible ways to achieve this: (1) use lightweight materials such as fiber ropes, or (2) increase the strength of steel rope so that it can be made thinner. There are several problems that must be solved if fiber rope is to be used as a substitute for steel wire rope: low axial stiffness that causes rope elongation with load, low adhesive wear and tear resistance, low fatigue life when subjected to constant cyclic bending due to damage occurring during heave compensation modes, internal heat buildup, very low and variable coefficient of friction due to rope coating, contamination and temperature. Therefore, steel wire rope is still effective for use in mooring line components in deep water. However, further strengthening of steel wire is required to overcome the weight penalty. Strengthening of steel wire can be achieved by increasing carbon content, adding alloying elements and increasing cold work [4-11]. A considerable amount of work has been carried out on micro-alloyed steel in the past years, particularly involving chromium, manganese and molybdenum additions [4-9]. The use of carbon contents up to 0.92% has been shown as having potential for enhancing the strength of rods for roping applications [10-11]. However, little work has been done towards improving the fatigue life and corrosion resistance of steel wire ropes for offshore industry having carbon contents higher than 0.92%. One of the fundamental problems is that there is the limit to increase the strength of steel wire because the strength of the patented wire is increased, but drawing amount is reduced with increasing carbon content. Another problem is that it is difficult to meet the fatigue characteristics due to the embrittlement that originates from cementite dissolution. Furthermore, the mechanism of embrittlement is still not clear, since the mechanism of cementite decomposition has been discussed without a common consensus being reached [12].

In the process of strengthening, the marine environmental factors should also be considered because the effect of the marine environment on the fatigue life of the ropes increases rapidly with the depth of seawater. Moreover, higher tensile strength steels are more susceptible to the environment [13, 15]. Steel wire rope suffer degradation by stress corrosion and fretting, particularly ropes used in mooring at sea. Fretting can be exacerbated not only by the presence of such an aggressive environment such as seawater, but also by the continuous cyclic loading through wave movement over the length of the rope during its entire lifetime [14]. These factors result in a significant reduction in the life of the ropes. Thus, the challenge is to develop ropes with increased strength, and at the same time to reduce the harmful effects of environmental factors.

In the present research, an investigation has been conducted to determine the types of degradation that may occur when high strength steel ropes are used for mooring lines, and to explore a new coating technology and steel strengthening process to overcome these degradations.

1.2 Problem Statement

To fulfill the increased demand in the mooring application, new technology development should be made in three areas: high strengthening technology, good fatigue property in high strength steels, and excellent corrosion resistant coating technology. However, several problems associated with these developments exist:

a) Since the effect of the marine environment on the fatigue life of ropes increases rapidly with the depth of seawater, higher tensile strength steels have a shorter life span, owing to their increased susceptibility to the environment. The mechanism is still not clear and there is no method to date on how to solve such a problem.

b) Steel wire rope is greatly affected by fretting-induced corrosion, which becomes more severe with increasing sea water depth. However, there is a lack of understanding on the effect of increasing the tensile strength on fretting-induced corrosion and also on the methods to reduce this fretting harmful effect.

c) It is well-known that anti-corrosion products contribute to corrosion inhibition, but in the case of severe fretting, their role is reduced because the anti-corrosion material is easily removed. Until today, there is no research on how to reduce this fretting harmful effect, or development of a new coating technology to produce tough anti-corrosion products having high fretting resistance with increased exposure to sea water.

d) It is well established that the life span of mooring ropes is primarily dependent on the corrosion resistance of the zinc coating, but very few attempts were made to develop a new coating capable of increasing the corrosion resistance of steel wire ropes. This research is aimed to develop high tensile steel rope (2,150-2,250 MPa) with good corrosion resistance.

1.3 Objectives of the Research

To meet the current technology trend of offshore oil and gas production facilities, development of ropes having lighter characteristics and longer life span is required.

Therefore, the main objectives of this research are to develop steel ropes with high tensile strength and excellent corrosion resistance. The specific objectives are:

1. To investigate the effect of composition on strength and corrosion resistance of galvanized wire.
2. To investigate the degradation mechanism of high tensile strength (2,150 -

2,250 MPa) galvanized steel rope in sea water.

3. To develop a Zn-Al-Mg ternary alloy coating to enhance the corrosion resistance (3,000 salt spray hours) of steel ropes.

1.4 Scope of Work

In order to increase the strength of steel wires, used in the oil and gas industries, above 2,150 MPa and corrosion resistance over 3,000 salt spray hours, the study concentrates mainly on the following:

1. Enhancing the fatigue property and corrosion resistance of galvanized steel wire through control of steel chemical composition by varying the carbon content (0.87-0.98wt%) and alloying elements of Cr (0.58-0.60wt%) and Si (0.2~1.3wt%). This phase of research focuses on investigating:
   a) Tensile strength, torsion and delamination of galvanized steel wire
   b) Fatigue property and fracture behaviour of galvanized steel strand
   c) Formation of Zn-Fe alloy layer during hot dip galvanizing and its effects on the corrosion resistance of steel wire

2. Degradation mechanism of galvanized steel rope in sea water. This phase consists of examining:
   a) The effect of fretting and contact pressure among wires on the corrosion behavior of exposed steel ropes
   b) The corrosion behaviour based on wire position in the rope

3. Corrosion protection of rope in sea water by using newly developed zinc alloy coating. This phase of research looks at:
   a) The effects of Mg (0.5-5.0wt%) and Al (0.5-6.0wt%) contents on coating microstructure
   b) The effects of Mg and Al contents in the Zn alloy coating on the corrosion behaviour and corrosion product characteristics

process, (c) corrosion product having good adhesion, which improves resistance against fretting.

7. The lowest corrosion rate was obtained in the Zn-Mg-Al alloy coating having 1.0~3.0wt% Mg and Al content. Even by addition of a small amount of Mg and Al by 0.5wt%, the corrosion resistance, similar to the Zn-3.0wt%Mg-6.0wt%Al alloy coating was obtained. Over that wt.%, the improvement effect of corrosion resistance was not observed. The Zn-0.5wt% Mg-0.5wt% Al coating had an excellent corrosion resistance (3,144 hours in salt spray), which was 12 times higher than the pure Zn coating. It might be attributed to simonkolleite ($Zn_5(OH)_8Cl_2 \bullet H_2O$) found on the surface as the main element of the corrosion product.

8. The Zn-Mg-Al Alloy coating produced by the two-step galvanizing processes had very good corrosion resistance and fretting resistance due to the following reasons: (a) multi-layers have several different alloy phases. These alloy phases exert a synergistic effect in improving corrosion and fretting resistance, and (b) no cracks inside the coating during the coating and drawing process.

5.2 Recommendation for Future Work

As described previously, since rope degradation was the dominating factor for mooring, caused by fretting and corrosion, the investigation of the Zn-Al-Mg alloy coated rope life span is required.

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