CORROSION FATIGUE BEHAVIOR OF SHIP HULL STRUCTURAL STEELS

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ABSTRACT

This paper seeks to describe on corrosion fatigue behavior of ship hull structural steels mainly based upon the author's recent experimental results. First it is described on general view of corrosion fatigue strength and corrosion fatigue crack propagation behavior of high strength steels. Then it is presented on corrosion fatigue strength of ship hull structural steel in ballast tank environment. It is demonstrated that tar epoxy resin coating effect on corrosion fatigue strength of KA32(TMCP) steel is observed in lower nominal stress range. Corrosion fatigue crack propagation behavior of ship hull structural steels in cargo oil environment is also presented. Fatigue crack propagation rate for KA36(TMCP) and KAS steel is accelerated in the region where ΔK is above about 16MPa $m^{1/2}$ in the sour crude oil containing 400ppm H_2S. A couple of future problems on corrosion fatigue research of ship hull structural steels are also touched in brief.

KEYWORDS

Corrosion fatigue strength, Corrosion fatigue crack propagation behavior, Ship hull structural steel, Ballast tank environment, Tar epoxy resin coating, Cargo oil environment, Hydrogen sulfide, Brittle striation

INTRODUCTION

Recently much attention has been focussed upon the improvement of corrosion fatigue strength and the evaluation of corrosion fatigue life for ship hull structural steels under ballast tank and cargo oil tank environment. The advantages such as lighter structures, increasing design stress and saving welding time were brought by use of higher strength steels for ship hull structures. However, the structure became more susceptible to corrosion fatigue. To evaluate ballast tank life evaluation of corrosion fatigue strength for ballast tank members is necessary under sea water environment with high temperature and high humidity. To evaluate corrosion fatigue life of cargo oil tank members it is necessary to understand corrosion fatigue crack propagation behavior of ship hull structural steels under cargo oil environment containing hydrogen sulfide.
In this paper it is briefly summarized on corrosion fatigue behavior of ship hull structural steels under sea water and sour crude oil environment mainly based upon the author's recent experimental results. It is demonstrated that corrosion fatigue strength of KA32 (TMCP) steel can be improved by tar epoxy resin coating. It is also demonstrated that an acceleration of corrosion fatigue crack propagation rate for KA36(TMCP) and KAS steel is observed in the higher stress intensity factor range under sour crude oil environment.

CORROSION FATIGUE STRENGTH OF HIGH STRENGTH STEELS

Fig.1 shows the conventional S-N diagrams for four kinds of high strength steels obtained by ISIJ round robin test [1]. Based upon the obtained more than one thousand S-N diagrams including those shown in

Fig.1, it was concluded that corrosion fatigue strength of tested high strength steels were almost same in the number of cycles of $2x10^4$ to 10^7. Thus it has been experimentally confirmed that corrosion fatigue strength of high strength steel is almost same as that of mild steel [2,3]. This means that an improvement of corrosion fatigue strength cannot be expected by use of high strength steels for ship hull structures. In Fig.1 it can be also observed that the S-N curves are inclined to drop to the offshore structures' design curves such as AWS-XX Improved and UK DOE Basic Sea Water design curve and are anticipated to drop into the lower than these allowable design curves in the long term S-N curves. Therefore, countermeasures such as cathodic protection and coating are absolutely necessary for safety use of high strength steels for ship hull structures.

In fact it was experimentally confirmed that the S-N curves for cathodically protected T type welded specimens for HT80 dropped in the upper side of the AWS-X and DOE design curve [4]. To keep the marine structures' maintenance free for long term services the complete cathodic protection system must be developed. The system should be taken stress gradient on the corrosion fatigue strength of the large scaled members such as ship hull structures and the connected tubular joints for offshore structures into consideration.

The most of the fatigue design rules for offshore structures are based upon the S-N diagrams. However, it is anticipated that brittle failure might occur from the corrosion fatigue crack initiated from the small defects of the welded joints in the low temperature sea water. Therefore many corrosion fatigue crack propagation tests for high strength steels have been conducted in sea water environment. Crack propagation tests of HT80 base metal and welded joints were conducted in low temperature sea water. Crack propagation rate of HT80 base metal in 4^0C synthetic sea water was almost four times faster than that in air at room temperature. It was also clarified that corrosion fatigue crack propagation rate in the heat affected zone was slower than that of the base metal. The da/dN of the heat affected zone might be enhanced due to hydrogen, however the higher hardness and corrosion resistant martensitic structure gave a slower da/dN in heat affected zone [5]. More than six thousand da/dN～⊿K curves were obtained in an artificial sea water in the aforementioned ISIJ round robin test. The acceleration of the da/dN was observed in sea water environment [6].

Fig.1 S-N curves of four kind of high strength steels in synthetic sea water [Toyama et al.[1.]].

To evaluate corrosion fatigue strength and corrosion fatigue crack propagation rate of high strength steels we have to consider about corrosion fatigue variables such as environmental, mechanical and metallurgical variables [7]. The principal environmental variables are bulk solution chemistries, temperature, dissolved oxygen content and wet-dry alternation. Further studies are required for wet-dry alternation on corrosion fatigue behavior of ship hull structural steels. Among the mechanical variables mean stress, frequency, stress mode, stress wave form and stress concentration factor are important to evaluate. The extensive studies on effect of stress mode, stress history and random loading on corrosion fatigue strength of high strength steels provide the useful data for ship hull structural design. As aforementioned any improvement of corrosion fatigue strength can be expected for high strength steels in sea water environment, the development of corrosion resistant high strength steels with higher corrosion fatigue strength is strongly desired. Whereas it has been indicated that the characteristics of weld metal depend not only metallurgical factor but also is strongly influenced by welding parameters［8］. Among the metallurgical variables the subjects of plate thickness and residual stress should be particularly investigated.

CORROSION FATIGUE BEHAVIOR OF TAR EPOXY RESIN COATED SHIP HULL STRUCTURAL STEEL

Fig.2 shows the effect of tar epoxy resin coating on corrosion fatigue strength of the ship hull structural steel KA32(TMCP) plate notched specimen by push-pull fatigue testing[9]. The coating thickness is 200 μm and stress concentration factor of the plate specimen is 2.0. It is apparent that the effect of tar epoxy resin coating is observed in lower nominal stress range. An increase of corrosion fatigue life was 2.8 times higher than that of base metal specimen at nominal stress range of 199.8MPa. The lower the nominal stress range the coating effect increased. The influence of coating thickness with 50 to 300 μm on corrosion fatigue life was also investigated. The thicker the coating thickness the longer the fatigue life was. Impedance/time curves were taken for tar epoxy resin coated specimen with 50 to 300 μm thickness. Impedance of tar epoxy resin

Fig.2 S-N_f curve for tar epoxy resin coated specimen in artificial sea water［Ebara et al.[9.]］.

coated with 50 and 100 μ m dropped tremendously after few days exposure into an artificial sea water. While the impedance of 200 μ m and 300 μ m tar epoxy resin coated specimen did not drop after exposure for 6000hrs. The impedance dropped slightly after exposure for 10^4 hrs. However the dropping rate was not prominent. From these results it can be mentioned that tar epoxy resin deteriorates due to the change of water absorption after long term exposure in sea water. The deterioration of the tar epoxy resin coating at the notched area of the coated specimen was influenced by the repeated stress. The decrease of the impedance at the notched area was bigger than that at the plane area 〔Fig.3〕. These facts reached to the following mechanism of the deterioration of the tar epoxy resin coating. In higher nominal stress range corrosion fatigue crack initiate earlier at the notched area where stress concentrate and an improvement of corrosion fatigue strength cannot be expected when an interception effect against sea water disappear. The lower the nominal stress range an improvement of corrosion fatigue strength becomes to be observed by an interception effect due to the difficulty of crack initiation on the coating. An improving effect becomes to be smaller when water absorption rate increases and the coatings deteriorates as times go by. Since the deterioration of the tar epoxy resin coating is governed by the thickness of the coating, it can be mentioned that effective coating thickness to improve corrosion fatigue strength of the ship hull structures is at least 200 μ m. Considering the deterioration of the tar epoxy resin coating at the notched area, it can be easily reached to conclusion that the toe of the welded joints of ship hull structures is easily deteriorates due to the breakage and deterioration of the tar epoxy resin coating. To evaluate corrosion fatigue strength of the ballast tank members further studies on effect of sea water temperature on corrosion fatigue life of tar epoxy resin coated ship hull structural steels is necessary.

Fig.3 Impedance/Number of cycles curve for tar epoxy resin coated fatigue test specimen with 50 μ m thickness coating 〔Ebara et al.[9]〕

CORROSION FATIGUE CRACK PROPAGATION BEHAVIOR OF SHIP HULL STRUCTURAL STEELS IN CARGO OIL TANK ENVIRONMENT

Corrosion fatigue crack propagation tests for the ship hull structural steels and their welded joints were conducted in sour crude oil containing 400 ppm H_2S. The crack propagation rate of the ship hull structural steels such as KA32(TMCP) and KAS steel in sour crude oil containing 400 ppm H_2S was remarkably accelerated in the higher ⊿K region [Fig.4][11]. This acceleration was also observed on X65 line pipe steel in sour crude oil containing 1 to 4700ppm H_2S [12]. In the accelerated crack propagation area it was also found that the crack propagated predominantly on the cleavage fracture surface in association with brittle striation in the sour crude oil environment. The striation spacing per cycle, S obtained from the measured striation spacing⊿S versus ⊿K curve was well coincident with the da/dN ～⊿K curve in the accelerated crack propagation area. It can be assumed that hydrogen molecule (H_2) produced through the reaction of H_2S and H_2O in sour crude oil with ship hull structural steel turns into atomic hydrogen (H) ,which enters the plastic zone of the fatigue crack tip and accumulates there in large quantities causing the plastic zone to turn into the hydrogen embrittlement zone and thus resulting in acceleration of crack propagation rate as shown in Fig.5.Thus it can be concluded that the environmental enhancement of the fatigue crack propagation rate in sour crude oil is dependent on hydrogen evolved by reaction between H_2S and H_2O in the sour crude oil with structural steels. The crack propagation tests were also conducted for welded joints. The da/dN for weld metal (WM),heat affected zone (HAZ) and base metal (BM) in the sour crude oil were much faster than those in air[13]. The three stage crack propagation mechanism can be considered. In stage1 the fatigue crack opening is extremely small due to the compressive residual stress present in WM and HAZ. The corrosion products prevents of sour crude oil into the crack tip.

Fig.5 Schematic illustrations of corrosion fatigue mechanism in sour crude oil environment [Ebara et al.[11.]]

Fig.4 Fatigue crack propagation rate in sour crude oil (400 ppm H_2S) and in air [Ebara et al. [11.]]

Consequently, H_2S and H_2O are prevented from reaching crack tip and da/dN decelerated. In stage 2 the crack opening increases with associating fatigue crack propagation, causing the corrosion products itself to crack. Consequently, sour crude oil gradually reached fatigue crack tip, allowing da/dN to approximate to the da/dN in the corrosive environment. In stage 3 the crack opening is large enough to permit sour crude oil to constantly reach the fatigue crack tip causing the fatigue crack propagation to proceed in the corrosive environment. It is also considered that the acceleration of corrosion fatigue crack propagation rate of the welded joints in sour crude oil is due to the effect of an atomic hydrogen resulting from a reaction between steel welded joints and H_2S, and H_2O in sour crude oil. For HAZ of the CT specimen in the sour crude oil, the relation between brittle striation spacing and ⊿K shows a relatively good agreement with the da/dN ～ ⊿K curve in the region of high crack propagation rate as in the case of BM, showing the dominant influence of the brittle striation on the fatigue crack propagation behavior in the high ⊿K region in the sour crude oil environment. In this tests that the effect of sour crude oil containing 400 ppm H_2S on the fatigue life of the round notched bar specimen was pronounced in the higher stress region and obviously tended to decrease as decreasing the stress. It was also assumed that atomic hydrogen accumulated in the plastic zone at the fatigue crack tip accelerated the crack propagation rate and hence causing the round notched bar specimen to fail shorter in the sour crude oil than in air [11].

CONCLUDING REMARKS

This paper has briefly summarized on corrosion fatigue behavior of ship hull structural steels. To develop a reasonable fatigue life design and fracture control design for ship hull structures much more information is needed about metallurgical, mechanical and environmental variables which influence on corrosion fatigue behavior of high strength steels. It is recommended to evaluate corrosion fatigue crack initiation life at the notched area and the welded toe of the ship hull structural steels. A quantitative evaluation of an influence of tar epoxy resin coating on crack initiation and propagation of the coated specimen is also desired. Clarification of water absorption mechanism for the tar epoxy resin coating and of an improving effect corrosion fatigue behavior in lower stress and long term region is future problem to be solved. It is also recommended to study on the effect of H_2S concentration ,plate thickness and microstructure on crack initiation and propagation behavior of ship hull structural steels in sour crude oil environment.

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