Application of the Latest Technologies to Fatigue Strength Improvement

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Abstract

For improvement of fatigue lives, hull designers have been advised to improve the geometry of structural details, to reduce the general stress levels or to use some post-welding improvement method like toe grinding, TIG dressing or some types of hammer peening. Two latest technologies for improvement of the fatigue strength of hull structure are introduced and studied in this paper: one is from the material points of view and the other is from the fabrication points of view. From the material points of view, a new steel material (FCA-W steel) was developed around 2001, which showed an improved fatigue initiation life as well as an improved crack growth life both in base steel plate and welded joints, and a new alternative for fatigue life improvement was thus introduced although fatigue design has been traditionally based on the fundamental premise that the fatigue lives of welded structures are independent of the steel materials used and their strengths. By introducing this new steel, fatigue life can now be improved. Its effective application has also been studied in consideration of newly established S-N curves for this steel (FCA-W steel). From the fabrication points of view, ultrasonic peening has attracted attention as a fatigue strength improvement method. The ultrasonic peening method improves fatigue life owing to the compressive residual stress, a weld toe geometry improvement and the grain refinement that are caused by imparting impulses at the weld toe with radiused pins. Regarding the application to ship structure, its effective application has also been studied under various loads.

1 Introduction

We, three shipbuilders in Japan have introduced two latest technologies for improvement of the fatigue strength of hull structures: The application of high fatigue-strength steel to weldments (FCA-W steel) from the material point of view, and of the ultrasonic peening method (UP-method) to weld bead toes from the fabrication point of view. At fatigue design stage, hull designers have been advised to improve the geometry of the structural details to reduce the stress level, or to resort to some post-welding improvements like weld bead toe grinding or TIG dressing at fabrication stage because fatigue design has long been based on the fundamental premise that the fatigue strength of a welded structures is independent of the steel material use and its strength.

The former FCA-W steel will be applicable to be applied relatively high-stress areas in hull structure to improve its fatigue strength without any structural reinforcements only if the S-N curves of the FCA-W steel are newly established. In this study, the effects of FCA-W steel application instead of conventional steel on fatigue strength improvement are introduced, and several application studies during structural design carried out by three shipbuilders are shown summarizing its effective application proposals from the viewpoints of fatigue design.

The latter UP-method improves fatigue strength for weldments at fabrication stage by the compressive residual stress, a weld toe geometry improvement and the grain refinement caused by imparting impulses at the weld bead toe with radiused pins. Its effective applications under variable load are also studied through a series of fatigue tests envisaging its practical applications.

2 FCA-W Steel

FCA-W steel, a new steel material, was developed that showed an improved fatigue crack initiation life in weldments as well as an improved crack growth life in welded structures. For its practical applications, hull designers must newly establish the S-N curves of FCA-W steel approved by the classification societies as stipulated in the Common Structural Rules for Double Hull Oil Tankers (CSR-T) [1]. We have continued the joint research projects with Sumitomo Metal Industries and each of the classification societies: NK, DNV, and LRS.

Mechanism of FCA-W steel

Low carbon content is one of the main characteristic of FCA-W steel plates. The micro structure of FCA-W steel is a fine ferrite-bainite dual phase. As the result of dual phase structure, the yielding ratio is relatively small. One of the mechanisms at work in FCA-W steel to improve the fatigue strength of welded joints (weldments) is avoidance of the material notch effect by homogenous hardness distribution as shown in Fig.1. A material notch may occur at a steep change in hardness [2].

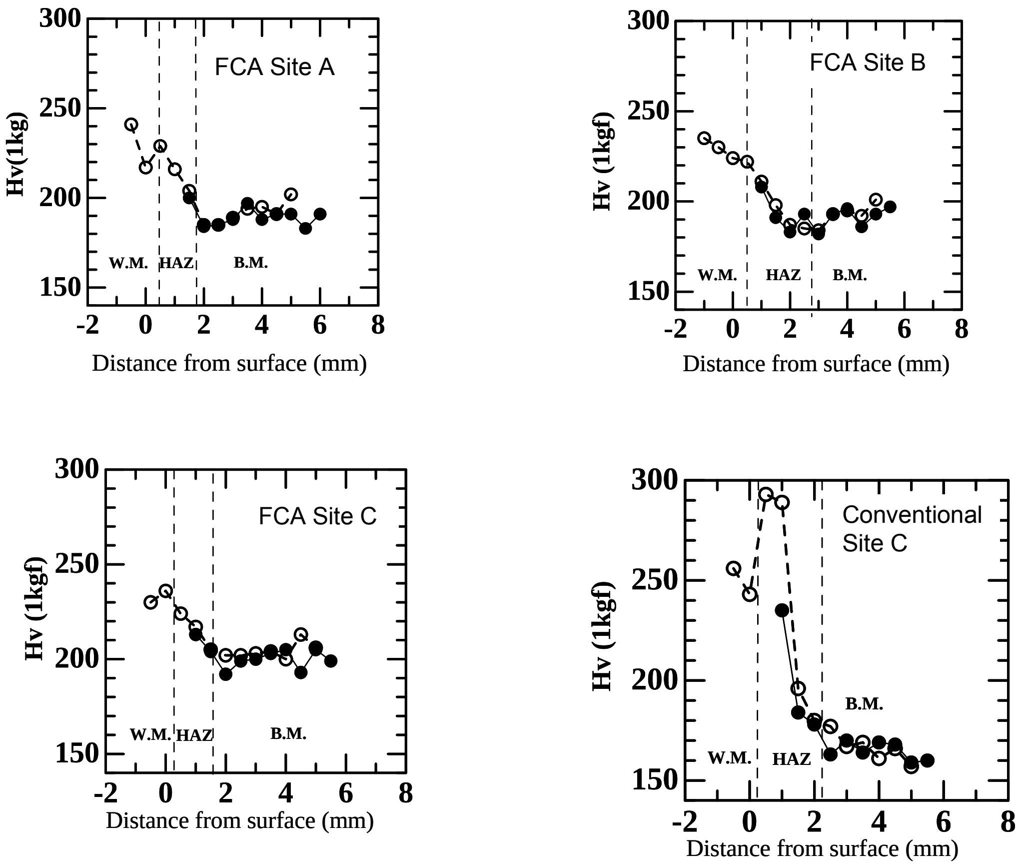

Fig.1 Hardness distribution of welded joints

Fatigue test

To establish the S-N curve, the fatigue testing of small scale test specimens was performed at a high stress ratio which is recommended in order to derive S-N data that are safe to use at all mean stress levels and to achieve test results that are representative of actual structures having a higher residual stress than that in the small scale test specimens. For assessment of test data, the test specimens made of conventional and FCA-W steels were prepared and fatigue tested. This makes it possible to perform a relative assessment of the fatigue strength that improves the basis for derivation of S-N curves keeping in mind all uncertainties that might be introduced during fabrication and fatigue testing. As a result of the earlier joint research project with NK, a tentative S-N curve adaptable to PrimeShip FA was newly established, discussing the result of the fatigue tests [3]. Figure 2 shows the fatigue life improvement in percentage by FCA-W application instead of the conventional steels against the stress ranges at a probability of occurrence of 10^{-4} in full and ballast load conditions based on the PrimeShip FA calculation results showing the superior characteristics of FCA-W steel for fatigue life improvement. Even in the higher stress ranges, fatigue life improvements by FCA-W steel application is considered to be approximately twice as the original fatigue lives of the conventional steels. This is the one of the advantages of FCA-W steel application. The design S-N curve of FCA-W steel for hot-spot stress range applied to cruciform joints with a similar geometry to the specimens obtained by other joint research project with DNV and LRS is shown in Fig.3 [4]. As shown in Fig.3, the differences between the FCA-W steel and the conventional steels are insignificant for the left part of the S-N diagram when approaching that of the low cycle region (high stress range). This indicates that the use of FCA-W steel should mainly be considered for structural details subject to wave type dynamics rather than and in areas subject to low cycle fatigue such as resulting from loading and unloading.

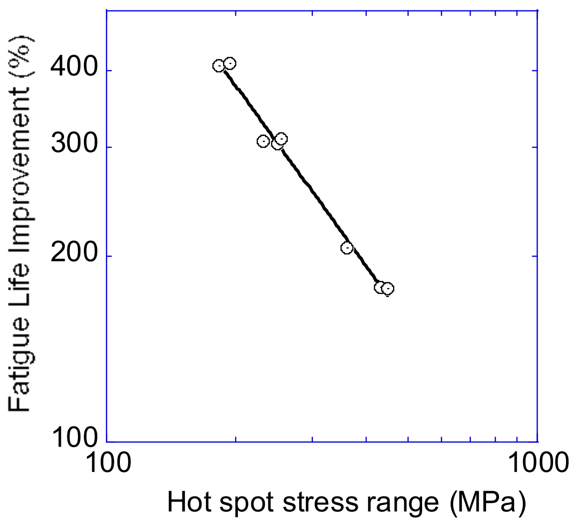

Fig.2 Relations between stress ranges and fatigue life improvement by FCA-W steel application

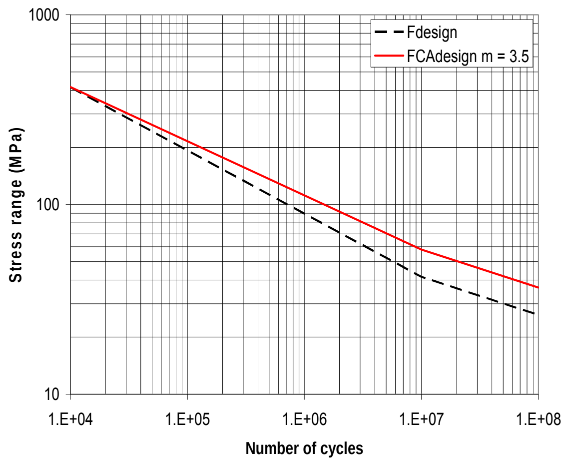

Fig.3 Design S-N curves of conventional and FCA-W steels

Figure 4 shows the fatigue test results for FCA-W steel with and without weld bead toe grinding performed by Sumitomo Metal Industries although these results must be further discussed in joint research projects with the classification societies. The fatigue life of FCA-W steel with weld bead toe grinding was improved furthermore twice or more than that of conventional steels. This means that FCA-W steel with weld bead toe grinding is also more effective for further fatigue life improvement on condition that full or partial penetration welding is applied to avoid root cracking.

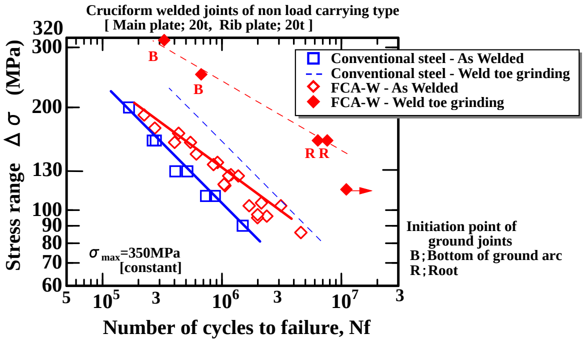

Fig. 4 Results of fatigue test of FCA-W steel with weld toe grinding

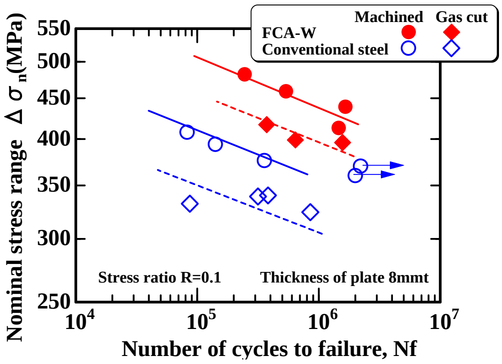

Fig. 5 Results of fatigue test of FCA-W steel for base metals

Application proposals

Several application studies on structural design carried out by three shipbuilders are shown summarizing its effective application proposals from the viewpoints of fatigue design.

Longitudinals in a cape size bulk carrier: A 350 x 125 x 10/21 T-type bottom longitudinal, and a 350 x 125 x 10/21 T-type side longitudinal were selected as examples of FCA-W steel application. These scantlings had already satisfied the fatigue life requirements by the Common Structural Rules for Bulk Carriers (CSR-B) [5]. In the CSR-B, as there are no specifications for FCA-W steel at present, the effect of application is estimated by relative comparisons between two fatigue life calculations based on the CSR-B replacing the B-curve in the CSR-B with F and FCA-W curves in Fig.3, respectively. As a result, fatigue life improvements of approximately 2.3-times became possible for the longitudinals by FCA-W steel application. From the viewpoint of fatigue design, structural optimization of longitudinals can be achieved by using FCA-W steel. In addition, structural redundancy by the use of FCA-W steels can be secured whenever hull designers conform to the original scantlings stipulated by the CSR-B.

Longitudinals in a VLCC: A 600 x 200 x 13/19 T-type bottom long , a 500 x 150 x 11/22 T-type side longitudinals provided in way of the draught line at normal ballast load and a 450 x 150 x 11/16 T-type side longitudinal provided in way of the draught line at full load were selected. In the case of CSR-T, the same estimation procedure for CSR-B was followed by using the design S-N curves in Fig. 3. With CSR-T, fatigue life improvements of approximately 2.5-2.8-times fatigue for the longitudinals became possible by FCA-W steel application. This means that the original longitudinals can still be used only by changing their material to FCA-W steels without any scantling increase even if their original design fatigue lives for conventional steels were 10-20 years, not satisfying the design life requirement stipulated by the Common Structural Rules. In addition, structural redundancy by the use of FCA-W steels can be furthermore secured whenever these scantlings are satisfied with the present fatigue requirements for the CSR-T.

Hatch corners on the upper deck of container ship: The fatigue life improvement with FCA-W steel was estimated by using the ABS Guideline. An improvement of approximately 1.8 times by FCA-W was obtained by comparison of the S-N curve for weld joints in Fig.3. As shown in Figure 5, because the fatigue life improvement with FCA-W steel for base metals by FCA-W application is relatively larger than that for weld joints, this improvement is considered to be more enhanced in base metal. FCA-W steel application will also be one of the alternative means for extending the fatigue life of hatch corners, replacing the practical measure of inserting a thicker plate in way of the corner in addition to its free edge grinding.

3 UP-method

The UP method improves fatigue life affected by imparting impulses given at the weld toe with radiused pins owing to the compressive residual stress, a weld toe geometry improvement, and the grain refinement as shown in Fig.6 [6]. Figure 7 shows the UP apparatus used in this study, UP500 system made by Integrity Testing Laboratory Inc.

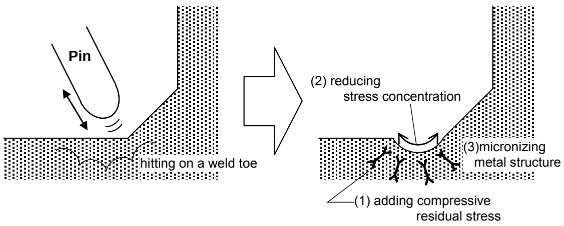

Fig.6 Schematic views of effects by UP-method

Fig.7 UP500 system

Fatigue tests for fillet and boxing weld joints by using cruciform joints without load bearing were performed at room temperature in order to confirm the effects of the UP-method on fatigue strength. The test was performed under three weld toe conditions: as weld, weld toe-grinding, and weld toe UP. The S-N data obtained for fillet welding joints are shown in Fig.8, and those for boxing weld in Fig.9. In Fig.8, the fatigue lives of fillet weld joints after UP are improved to the same levels of those after toe-grinding. In addition, the same improvement levels are seen to be obtained for the different plate thicknesses (16mm, 22mm, and 30mm) of specimens. As shown in Fig.9, because the slope of the S-N curve for UP is slower than compared to that for ‘as weld’, the improvement by UP for boxing weld is effective within the low stress ranges. It is also confirmed that the improvement by UP for fillet weld joints decreases as the stress ratio becomes larger as shown in Fig.10. Figure 10 shows the effects of overloads on fatigue strength for boxing weld joints with or without Ups. For the test specimens exposed to larger compressive load, the effects are reduced while the effects are maintained for those exposed to larger tensile loads.

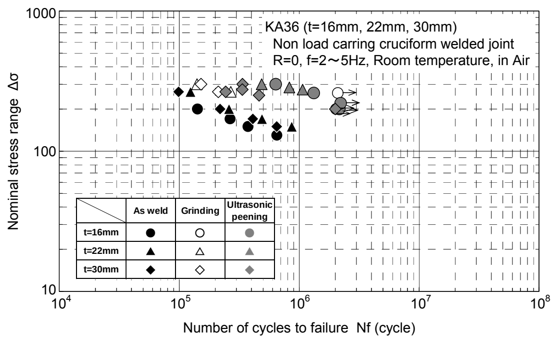

Fig.8 Fatigue test results for fillet weld joints

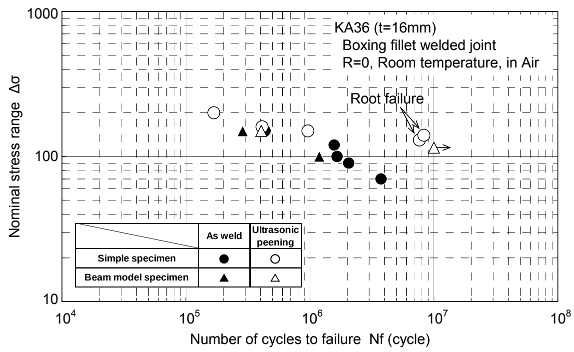

Fig.9 Fatigue test results for boxing weld joints

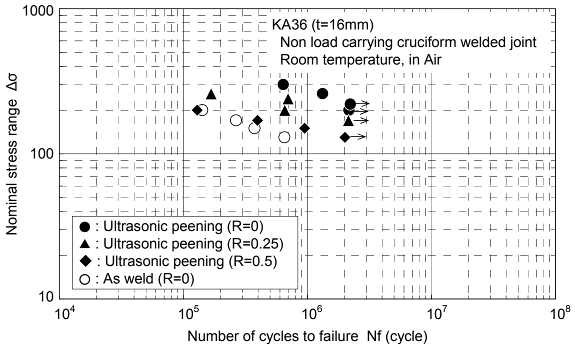

Fig.10 Effects of stress ratio on fatigue strength

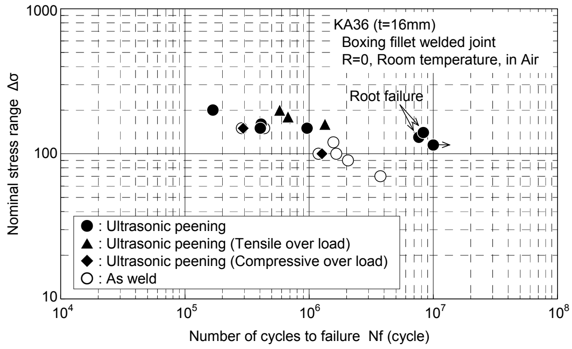

Fig. 11 Effects on over load on fatigue strength

In order to clarify the effect of stress ratio and load on the fatigue life improvement by UP, additional fatigue tests reproducing the change of load conditions before and after launching during the construction stage were performed on the assumption that UP would be carried out for the fillet weld joints in way of the upper deck exposed to changeable hull-girder loads. The relations between the applied stages of UP and loads for fatigue test condition, Case-1 and Case-2 are shown in Fig. 12. In Fig.12, Case-1 reproduces UP application in the building dock before launching, while Case-2, after launching. As shown in Fig.13, the same levels of fatigue lives as 'as weld' joints are observed for Case-1 (before loading), while the improvements of fatigue lives compared with UP at a stress ratio of R=0 are observed for Case-2 (after launching).

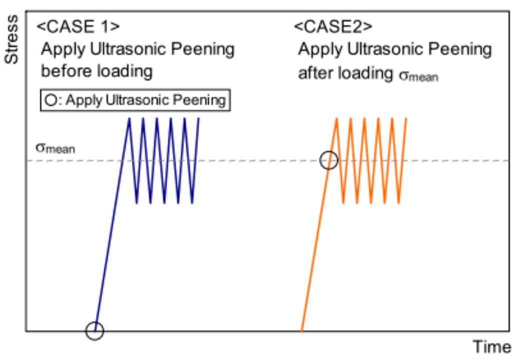

Fig.12 Loading cases for fatigue tests

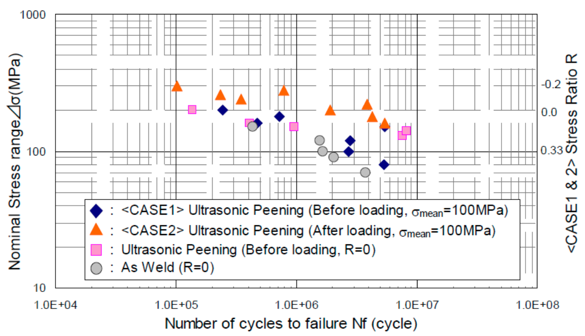

Fig. 13 Effects on application stage of UP

4 Conclusions

The applications of FCA-W steel and UP were introduced as the latest technology against fatigue strength improvement from the viewpoints of fatigue design and fabrication.

FCA-W steel

Effective application of FCA-W steel to stress-concentrated areas in hull structure can now be officially discussed at the structural design stages by using the newly established S-N curves approved by the classification societies. The designers can freely use FCA-W steel instead of the conventional steels without any scantling increase in order to improve fatigue life. This effective application will be further discussed through these practical application proposals in this study.

UP-method

The application of UP to weld toes is as effective as that to weld toe grinding on fatigue life improvement of the weld joints at fabrication stage. The stage and scope of UP application, however, must be considered at design stage to take full advantage of its effective use. The designers suggest applying UP especially to the weld joints in way of the upper deck exposed constantly to hull-girder still-water hogging moments in container and LNG carriers as an effective application.

Acknowledgement

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