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ABSTRACT

Recently, the strength of the hull structure including fatigue strength has seen significant improvement because of application of IACS CSR (Common Structure rule), developed by IACS. Various methods which can increase the fatigue strength at welded joints are suggested, since the damage morphology on the recently welded structures was observed to be primarily fatigue failure. In Shipbuilding industry, smoothening of the welding bead toe by grinding is the method that is customarily adopted in order to increase fatigue strength. And recently, peening treatment at the welding bead has also been adopted. The peening treatment can reduce stress concentration by smoothening of the welding bead toe, and a compressive residual stress field generated by the impact of peening.

In case of generating compressive residual stress by impact, the same effect could be expected by shot blasting, which is the steel surface treatment before painting.

In this study, the condition of the residual stress generated at welding toe by shot blasting was investigated, and then from results of the fatigue test, the increase in fatigue strength due to residual stress is verified.

1. INTRODUCTION

In December 2013, IACS “the International Association of Classification Societies” adopted a new set of rules called “the Common Structural Rules for Bulk Carriers and Oil Tankers (CSR BC & OT)”. The CSR BC & OT harmonised requirements can be found in the Common Structural Rules for Bulk Carriers (CSR-BC) and Common Structural Rules for Oil Tankers (CSR-OT). The requirements in the CSR BC & OT apply to bulk carriers of length 90 m or more and double hull oil tankers of length 150 m or more, whose contracts for construction are dated on or after 1 July, 2015. All IACS member classification societies have been required to enforce the CSR BC & OT requirements after they officially took effect on 1 July, 2015.

The requirements of CSR are based on a ship trading in the North Atlantic wave environment for its entire design life 25 years. Since those design conditions of CSR are more severe than the former independent classification rules, the hull structural strength must be severely reinforced compared to the ships that were constructed according to the former rules.

Especially, fatigue strength assessment is required for a lot of structural members by using very fine mesh FE model for the CSR-BC&OT applicable ships. Hence, the necessity of huge reinforcements depends on the result of the assessment, even if no damage has been reported at those locations.

Various methods which can increase the fatigue strength at welded joints are suggested since the damage morphology on the recently welded structures was observed to be primarily fatigue failure. In Shipbuilding industry, smoothening of the welding bead toe by grinding is the method that is customarily adopted in order to increase fatigue strength. Furthermore, according to rule [1] grinding helps improve fatigue life by about two times. Additionally, as defined in CSR-BC&OT, similar to grinding, peening treatment can also increase the fatigue strength. Moreover, High Frequency Mechanical Impact (HFMI) [2] is being actively studied as one of the methods to increase fatigue strength. However, in accordance with CSR-BC&OT, inside bulk cargo holds, those treatment methods are not permitted as the post-weld treatment and the calculated fatigue strength cannot be increased at design stage.

Peening treatment at the welding bead toe has technically two effects. Firstly, the peening treatment can reduce stress concentration by smoothening of the welding bead toe, and secondly, a compressive residual stress field is generated by the impact of peening. These two effects can synergistically lead to increase in fatigue strength. In case of generating compressive residual stress by impact, the same effect could be expected by shot blasting, which is the steel surface treatment before painting.

Shot blasting is to be carried out in a ballast tank according to PSPC "Performance Standard for Protective Coatings" which has been adopted by IMO in 2006 and the rule change of SOLAS regulations II-1/3-2 that enhances PSPC. Furthermore, recently, shot blasting has been widely adopted for the treatment in other cargo holds including ballast hold. Thus, shot blasting has generally become part of the construction process and is carried out in the painting building after hull block assembly. Shot blasting is expected to have effects similar to peening since the steel surface is blasted upon by solid particles. Additionally, it is required to carefully carry out shot blasting treatment for welding bead, since it is presumed that the adequate compressive residual stress field generated contributes to increase in the fatigue strength at the welding bead toe.

As described above, it is presumed that the fatigue strength at the weld bead treated by shot blasting increases more as compared to as-welded condition, as a consequence of the generation of compressive residual stress caused by shot blasting. In other words, the current classification rules are too conservative and demand unreasonably high quality, since the merits towards the fatigue strength assessment are not considered in the rules. The advantages of the shot blasting before painting towards the improvement of fatigue strength have been investigated by Hensel [3] and Gericke [4].

In this study, the condition of the residual stress at welding toe by shot blasting was investigated, and then from results of the fatigue test, the increase of fatigue strength due to residual stress is verified.

2. MEASUREMENT OF RESIDUAL STRENGTH AT THE WELD TOE

2.1 TEST SPECIMENS

T-joint is made as test specimens. The materials of the test specimens are mild steel for shipbuilding "KA" and higher tensile steel for shipbuilding "KA36". Chemical component and material properties of applied steels are shown in Tables 1 and 2, respectively. Base plate specimens of thicknesses 15mm and 25mm are used. Attached plate thickness is 15mm. Applied specimens are listed in Table 3.

Table 1 Chemical component of applied materials (wt%).

Grade (Thickness)	C	Si	Mn	P	S	Cu	Ni	Cr	Al	Ti	C_{eq}
KA (15mm)	0.019	0.09	0.65	0.020	0.08	-	-	-	-	-	30
KA (25mm)	0.015	0.20	1.01	0.016	0.08	-	-	-	-	-	32
KA36 (15mm)	0.016	0.22	1.05	0.021	0.08	0.01	0.01	0.02	0.032	0.02	34
KA36 (25mm)	0.016	0.23	1.05	0.020	0.07	0.02	0.01	0.02	0.025	0.02	34

*C_{eq}: Carbon equivalent.

Table 2 Mechanical properties of applied materials.

Grade (Thickness)	Yield strength [N/mm²]	Tensile strength [N/mm²]	Elongation [%]	Charpy energy at 0 °C [J]
KA (15mm)	293	442	31	-
KA (25mm)	331	463	27	-
KA36 (15mm)	411	530	22	192
KA36 (25mm)	383	520	25	244

As shown in Fig.1, a T-joint of length 1000mm is constructed and then cut into specimens of length 200mm. T-joint is welded by horizontal fillet weld method by CO_2 Arc welding (Welding current = 280A, welding voltage= 32V, welding speed = 35cm/min, weld length = 5mm, welding wire = PL-22 (Nippon Steel & Sumikin Welding Co., Ltd.)). The three test specimens are T-joint in as-welded condition, treated by shot blasting and treated at the weld toe by Portable Pneumatic needle-Peening. In addition, before cutting as 200mm of the test specimens, the shot blasting was carried out in conditions similar to that of actual vessels by the workers who are in charge of the shot blasting for actual vessels in the shot blasting building. Then, the residual stress around the weld toe was measured.

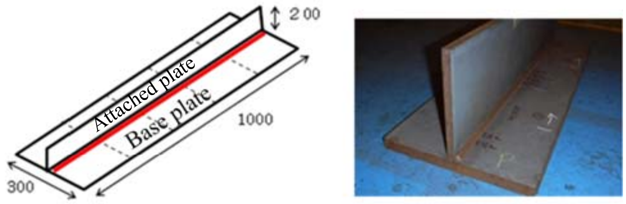


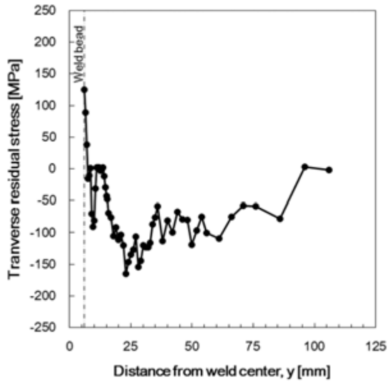
Fig.1 Specimen configuration used.

Table 3 Specimens used.

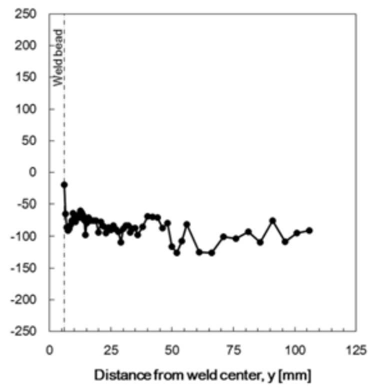
ID	Name	Treatment	Material	Base Plate Thickness
1	M15W	As welded	KA	15mm
2	M15B	Blast	KA	15mm
3	M15P	Peening	KA	15mm
4	H15W	As welded	KA36	15mm
5	H15B	Blast	KA36	15mm
6	H15P	Peening	KA36	15mm
7	M25W	As welded	KA	25mm
8	M25B	Blast	KA	25mm
9	M25P	Peening	KA	25mm
10	H25W	As welded	KA36	25mm
11	H25B	Blast	KA36	25mm
12	H25P	Peening	KA36	25mm

2.2 THE RESULT OF RESIDUAL STRESS MEASUREMENT

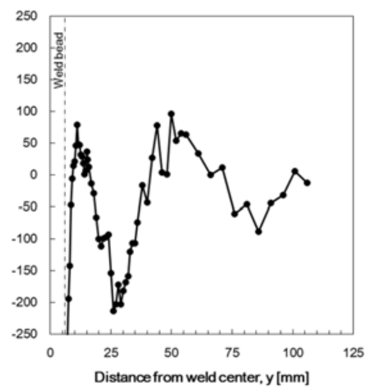
The residual stress was measured by Portable X-ray Residual Stress Analyzer (μ-X360s, Pulstec Industrial Co., Ltd.) [5] which employs X-ray diffraction by single exposure (cosα method). The measurement results are as follows. The horizontal axis indicates the distance from the bead and the vertical axis indicates the residual stress.



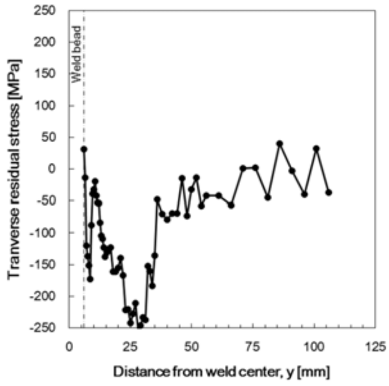
(a) Specimen M15W (As welded, KA, 15mm)



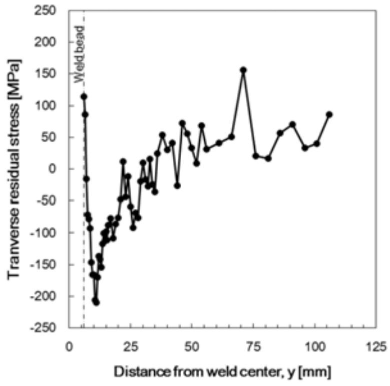
(b) Specimen M15B (Blasted, KA, 15mm)



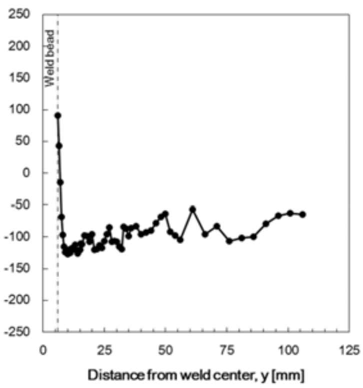
(c) Specimen M15P (Peening, KA, 15mm)



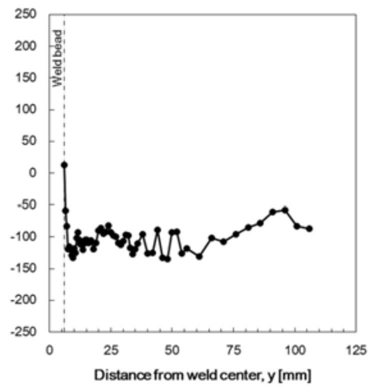
(d) Specimen H15W (As welded, KA36, 15mm)



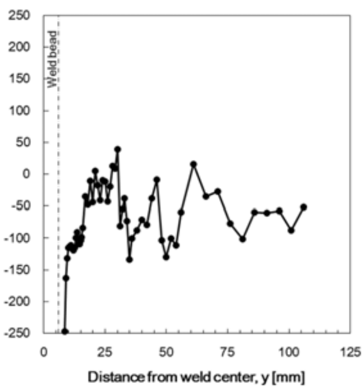
(g) Specimen M25W (As welded, KA, 25mm)



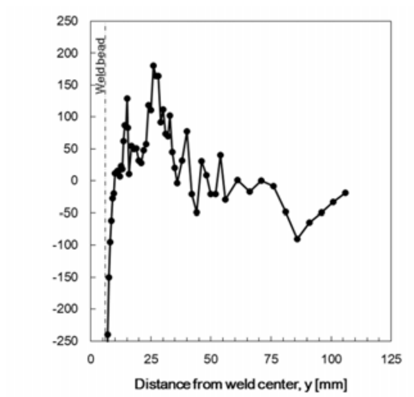
(e) Specimen H15B (Blast, KA36, 15mm)



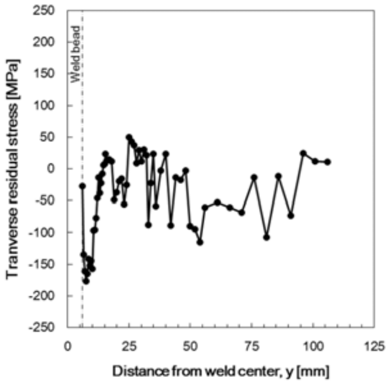
(h) Specimen M25B (Blast, KA, 25mm)



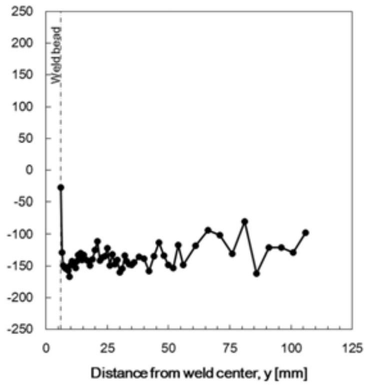
(f) Specimen H15P (Peening, KA36, 15mm)



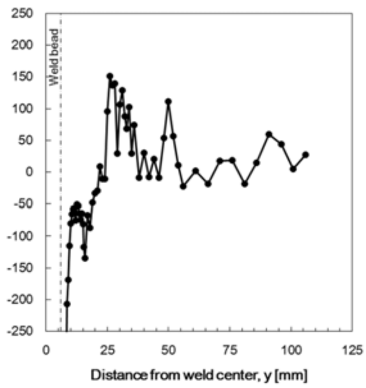
(i) Specimen M25P (Peening, KA, 25mm)



(j) Specimen H25W (As welded, KA36, 25mm)



(k) Specimen H25B (Blast, KA36, 25mm)



(l) Specimen H25P (Peening, KA36, 25mm)

Fig. 2 Measured residual stress distributions.

From the result of residual stress measurement shown in Fig.2, it can be observed that the tension residual stress exists around the weld toe of as-welded condition except (j) (as welded, KA36, 25mm). There was found to be such a tendency, although there is possibly some measurement error. Compression residual stress field is generated by shot blasting at the area away from the weld toe unlike as-welded. Conversely, significant compression residual stress field is generated at the weld toe of the test specimen treated by peening.

As described above, it is presumed that the fatigue strength of the specimen treated by shot blasting is more as compared to the as-welded specimen. Moreover, since the compression residual stress field is generated throughout the area slightly away from the weld toe, it is presumed that the fatigue crack growth speed is slower than the as-welded condition.

3. FATIGUE TEST

3.1 TEST PIECES FOR THE FATIGUE TEST

As described above, in order to provide evidence for the presumption that the fatigue strength of the specimen treated by shot blasting is more as compared to the as-welded specimen, three-point bending fatigue test was carried out by using T-joint specimens which were constructed similar to the specimens used for the residual stress measurement. Fatigue test specimens are listed in Table 4. The test pieces for the fatigue test were cut as 30mm of the length.

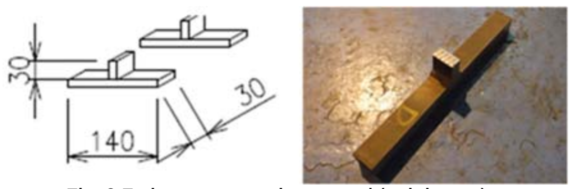


Fig. 3 Fatigue test specimen used (unit in mm).

Table 4 Fatigue test specimens.

Name	Treatment	Material	Base Plate Thickness
M15W	As-Weld	KA	15mm
M15B	Blast	KA	15mm
M15P	Peening	KA	15mm
H15W	As-Weld	KA36	15mm
H15B	Blast	KA36	15mm
H15P	Peening	KA36	15mm
M25W	As-Weld	KA	25mm
M25B	Blast	KA	25mm
M25P	Peening	KA	25mm
H25W	As-Weld	KA36	25mm
H25B	Blast	KA36	25mm
H25P	Peening	KA36	25mm

3.2 THE METHOD OF FATIGUE TEST

Three-point bending fatigue strength was carried out by using Servo hydraulic Fatigue Testing System. This test was generally carried out based on ISO/TR 14345:2012 [6]. The main test conditions are shown below;

- Stress ratio: 0.05
- The nominal stress range at the weld toe: as shown in Table 5.
- The number of repetitions was censored at 10^7 times.

Table 5 The nominal stress range for each specimen

Name	The nominal stress range at the weld toe					
	100 Mpa	125 Mpa	150 Mpa	200 Mpa	250 Mpa	350 Mpa
M15W	--	--	O	O	O	O
M15B	--	--	O	O	O	O
M15P	--	--	--	O	O	O
H15W	--	--	--	O	O	O
H15B	--	--	--	O	O	O
H15P	--	--	O	O	O	O
M25W	O	--	O	--	--	O
M25B	O	--	O	O	--	O
M25P	O	--	O	--	--	O
H25W	O	--	--	O	--	O
H25B	--	O	O	O	--	O
H25P	--	--	--	O	--	O

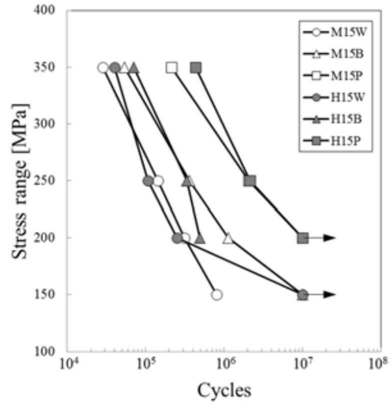


Fig. 5 S-N curves (base plate thickness: 15mm)

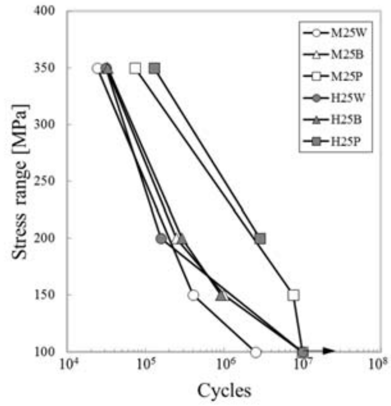


Fig. 6 S-N curves (base plate thickness: 25mm)

3.3 THE RESULT OF FATIGUE TEST

The fatigue test was carried out in accordance with the above. The crack had occurred at welding toe as shown in Fig.4. Figures 5 and 6 show the result of fatigue test plotted on the S-N curve.

Fig. 4 Cracked specimens

From the result of fatigue test, it can be confirmed that the test piece treated by peening has highest fatigue strength, followed by Shot Blasting and finally as-welded condition. In addition, it is also confirmed that there is no significant difference in behavior due to change in material and base plate thickness. Subsequently, it has become evident that the fatigue strength of the test specimen treated by shot blasting is higher than in as-welded condition. At the same time, as these effects are not considered at design stage, structural members treated by shot blasting has higher fatigue life than expected at design stage.

4. SUMMARY

The summary of knowledge obtained from this study describes as follows.

(1) Shot blast treatment generates compressive residual stress in a wider area around the weld toe of T-joint than in as-welded condition and peening treatment.

(2) Peening generates significant compressive residual stress field at the weld toe treated.
(3) From the result of three-point bending fatigue test, the fatigue strength of the weld toe treated by shot blasting is higher than in as-welded condition.
(4) There is no considerable difference in behaviour between mild steel (KA) and higher tensile steel (KA36).

The following issues are to be addressed in the next stage. An S-N curve considering the above effects is to be created. The extent of variability of the shot blasting effect that is to be taken into consideration should be studied. The fatigue strength of T-joint weld receiving a repetitive axial force is to be verified.

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