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Fatigue Strength of High Manganese Non-magnetic Steel and Carbon Steel Welded Butt Joints †

- Investigation for Applying Dissimilar Materials to Steel Structures (Report II) -

Eiji NAKAJI*, You Chul KIM**, Yoshihiro NAKATSUJI*** and Kohsuke HORIKAWA****

Abstract

The fatigue strength of a dissimilar material welded butt joints of high manganese non-magnetic steel and SS400 carbon steel (hereafter referred to as DMW joints) was almost the same with that of a welded butt joints of similar SS400 carbon steel. The fatigue strength of the DMW joints exceeded the fatigue design standard curve of JSSC (Japanese Society of Steel Construction) for SS400 carbon steel welded butt joints. From the viewpoint of the fatigue design, the DMW joints could be treated the same as welded butt joints of similar SS400 carbon steel in which the strength was lower than that of high manganese non-magnetic steel,. Significant hardening or softening was not found in the heat affected zone.

KEY WORDS: (High manganese non-magnetic steel) (Dissimilar materials welded joints) (Fatigue strength) (Fatigue life) (Fatigue design) (Hardness)

1. Introduction

The research and development of magnetic levitation vehicle systems (linear motor car), nuclear fusion reactors, etc. utilizing magnetic technology have progressed from the stage of basic studies to that of studies for practical use. High manganese non-magnetic steel (hereafter referred to as high Mn steel) is rather expensive compared with structural carbon steels, so when applying high Mn steel to the structures, means of reducing the fabrication costs are required in construction.

When paying attention to steel structures for magnetic levitation vehicle systems, the distance requiring non-magnetic properties is considered to be within about 1.5 (m) from the super-conductive magnet [1]. So, it is considered that a hybrid structure in which high Mn steel is partially adopted for the portion which really requires non-magnetic properties and carbon steel is adopted for the other portions. In such cases, dissimilar material welded butt joints of high Mn steel/carbon steel (hereafter referred to as DMW joints) are indispensable. However, there has not been any study of the fatigue strength of the DMW joints.

Before applying the DMW joints to such structures, it is necessary to confirm the mechanical properties and fatigue strength of these joints. The DMW joints were made, and mechanical properties of these joints were investigated [2]. According to the results, the DMW joints showed excellent penetration without weld defects such as blowhole, crack and so on. Excellent bending ductility was demonstrated without cracking [3].

In this study, the fatigue strength of the DMW joints is examined by fatigue tests, with the intention of applying these joints for the structures such as the steel bridges of magnetic levitation vehicle systems.

2. Experiment

2.1 Materials

Table 1 shows the chemical composition and mechanical properties of the base metals. The high Mn steel has a chemical composition with 0.25% C and 25% Mn. This steel is produced by reducing the C down to 0.25% to alleviate hardening during drilling, and by adding 25% Mn to stabilize the austenitic phase and confer non-magnetic properties. SS400 is used as the carbon steel.

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Table 1 Chemical composition and mechanical properties of base metals.

Designation	Plate thick-ness(mm)	Chemical composition (mass%) C (%)	Si (%)	Mn (%)	P (%)	S (%)	Mechanical properties YP (Mpa)	TS (Mpa)	El. (%)	vEo (J)
High Mn steel (0.25%C-25%Mn)	9	0.27	0.29	24.89	0.022	0.002	415*)	829	53	—
	16	0.25	0.27	25.02	0.019	0.001	303*)	774	61	216
Carbon steel (SS400)	9	0.12	0.23	1.02	0.015	0.003	291	434	31	—
	16	0.12	0.23	1.02	0.015	0.003	298	441	33	143

*) 0.2%YS

Table 2 Welding condition.

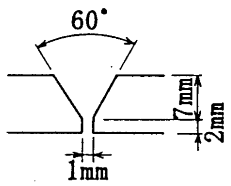
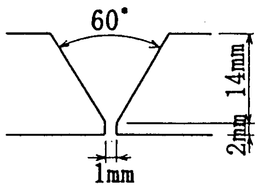
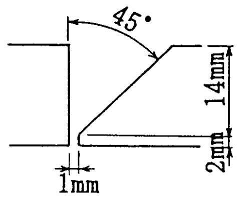
Welding process	MAG		
Plate thickness (mm)	9	16	
Shape of groove	 Carbon steel High Mn steel Single V	 Carbon steel High Mn steel Single V	 Carbon steel High Mn steel Single bevel
Heat input (kJ/cm)	21.6～24.7 (270A , 28～35V , 21～23 cm/min)		
Shielding gas	Ar + 20%CO_2 (25l/min)		
Preheating	None		
Interpass temp.(℃)	≦ 150		

Table 3 Chemical composition of filler wire.

Welding process	Diameter (mm)	Chemical composition (mass%) C	Si	Mn	P	S	Ni	Cr
MAG	1.6	0.40	0.59	13.30	0.007	0.007	9.14	2.72

2.2 Welding conditions

Table 2 shows the welding conditions.

MAG welding is performed without pre-heating and post-heating with single V and single bevel grooves. For the specimens with a plate thickness of 9 (mm), the welding sequence is such that the 1st layer is welded from the surface, and after back chipping, the 2nd layer is welded from the back face. Moreover, for the specimen with a plate thickness of 16 (mm), with both single V and single bevel grooves, the 1st to the 3rd layers are welded from the surface, and after back chipping, the 4th and 5th layers are welded from the back face.

Table 3 shows the chemical composition of the weld wire for high Mn steel.

2.3 Fatigue tests

Figure 1 shows the features of the specimen.

Fatigue tests are performed for the following two series:

(1) WJ series

① WJ-1: high Mn steel / SS400 DMW joints (with weld reinforcement)

② WJ-2: high Mn steel / SS400 DMW joints (without weld reinforcement)

③ WJ-3: high Mn steel / high Mn steel SMW joints (with weld reinforcement)

④ WJ-4: high Mn steel / high Mn steel SMW joints (without weld reinforcement)

where, SMW indicates similar materials joints.

(2) BM series

① BM-1: high Mn steel base metal (with mill scale)

② BM-2: SS400 base metal (with mill scale)

BM-1 and BM-2 are directly machined from the base metal. WJ-1 to WJ-4 are cut out by gas cutting in a rectangular shape with a width of 60 (mm) from the portion where no weld defects are detected in the radiographic inspection after the welding. The specimens are machined so that the weld metal may lies in the center of the specimen. Moreover, the weld reinforcement of WJ-2 and WJ-4 is removed by grinding away 0.5 mm on both the surface and the back face.

Fatigue tests are conducted by applying a tensile pulsating load (stress ratio R = 0) as repetitive a load, with sine wave and frequency of 4 to 15 (Hz). The fatigue life is defined as the number of cycles up to fracture of the specimen.

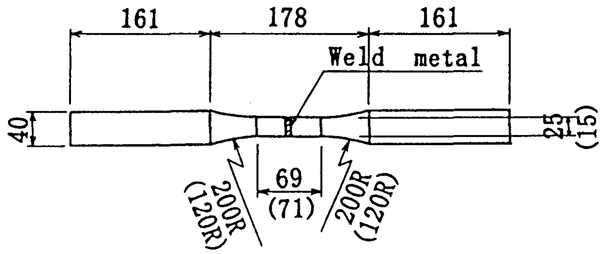


Fig.1 Configuration and dimensions of fatigue specimen.

3. Results and Discussion

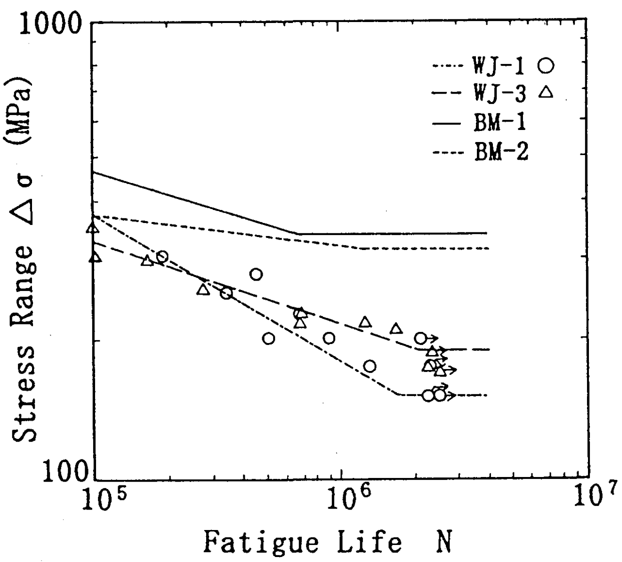
3.1 Fatigue strength

Figure 2 shows fatigue test results of BM series and WJ series.

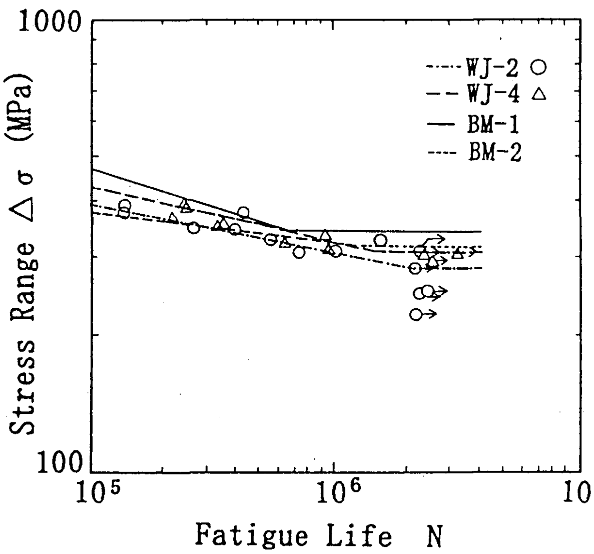
3.1.1 Welded joints with weld reinforcement (WJ-1 and WJ-3)

Figure 2 (a) shows S-N curves of WJ-1, WJ-3 and BM series (BM-1 and BM-2). The fatigue strength at 2×10^6 times (hereafter referred to as fatigue strength) of WJ-1, WJ-3, BM-1 and BM-2 is 150, 190, 340 and 320 (MPa), respectively.

According to the results, no great difference in fatigue strength between the high Mn base metal (BM-1) and the SS400 base metal (BM-2) is observed. The fatigue strength of the DMW joints (WJ-1) and of the SMW joints (WJ-3) is about 45(%) and 60(%) of the fatigue strength of SS400 base metal (BM-2), respectively.

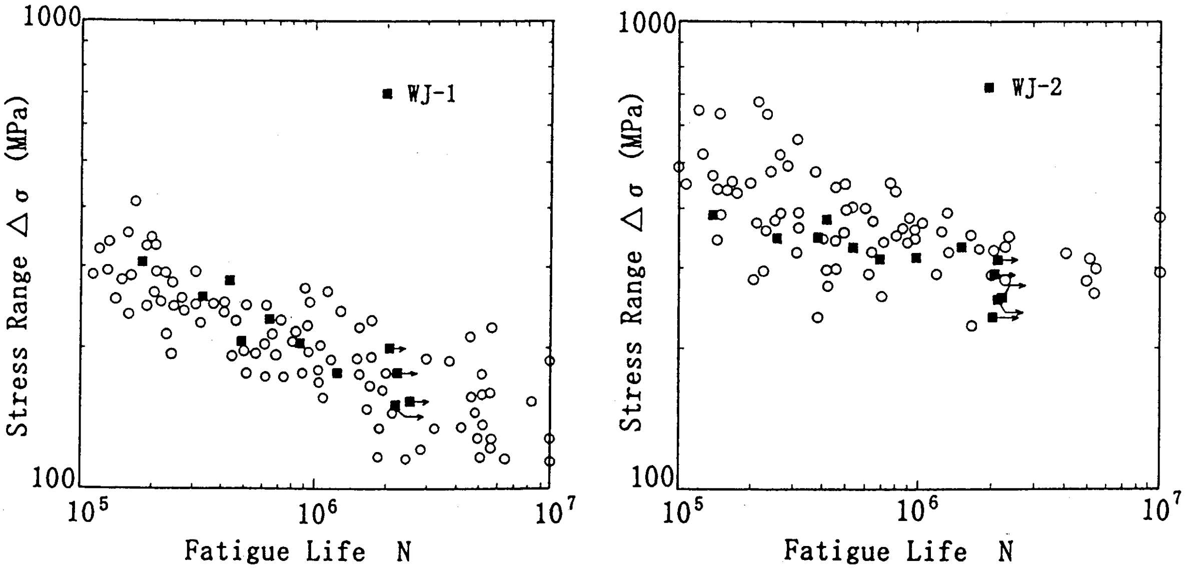


(a) With weld reinforcement.



(b) Without weld reinforcement.

Fig.2 Fatigue test results.



(a) With weld reinforcement.

(b) Without weld reinforcement.

Fig.3 Comparison of fatigue test results of dissimilar materials welded joints with similar materials welded joints of carbon steels.

WJ-1 and WJ-3 are fractured at the toe of weld reinforcement. This is probably because of the stress concentration at the toe of weld reinforcement. The fatigue strength of the welded joints with weld reinforcement, which largely depends on the shape of the toe of weld reinforcement, shows a large dispersion in test results compared with the base metal and the welded joints without weld reinforcement described in the next paragraph.

The inclined part in the S-N diagram (Fig.2(a)) is expressed by the following equation using the data with the stress range exceeding the fatigue strength at 2×10^6 times, among the fractured samples. In the equation, the stress range (*log* $\Delta\sigma$) is treated as an independent variable and the fatigue life (*log N*) is treated as a dependent variable.

$$logN = -m\ log\Delta\sigma + C \qquad (1)$$

The fatigue limit is decided on the basis of the test results of the several stress ranges.

3.1.2 Joints without weld reinforcement (WJ-2 and WJ-4)

Figure 2 (b) shows S-N curves of BM series (BM-1 and BM-2), WJ-2 and WJ-4. The fatigue strength of WJ-2 and WJ-4 are 290 and 310 (MPa), respectively. The fatigue strength is obtained in the order: ① high Mn base metal (BM-1), ② SS400 base metal (BM-2), ③ SMW joints (WJ-4), ④ DMW joints (WJ-2), and the fatigue strength of WJ-2 and WJ-4 is about the same as that of high Mn base metal and SS400 base metal.

BM-1 (340) > BM-2 (320) > WJ-4 (310) >
WJ-2 (290 (in MPa))

In WJ-2, fracture is recognized both in the SS400 base metal and weld metal. However, in WJ-4 all fracture is confirmed to the weld metal.

From Table 1, it is shown that the yield stress of SS400 base metal and of the high Mn base metal with a plate thickness of 9 (mm) are about 290 and 400 (MPa), respectively. On the other hand, the yield stress of weld metals using welding wire for high Mn steel in the WJ series is almost the same as that of SS400 base metal. Therefore, yield stress is the lowest at the SS400 base metal or welded metal in WJ-2 and the lowest at the welded metal in WJ-4. So, it can be estimated that a plastic area spread from there and fracture occurred.

3.1.3 Comparison with similar materials welded butt joints of carbon steel

Figure 3 shows the fatigue test results of the DMW joints in comparison with the tests results of similar materials butt joints of carbon steel conducted in the past [4]. The experimental results of the DMW joints are in the range of the deviation of test results of similar materials welded butt joints of carbon steel, both with weld reinforcement (Fig. 3(a)) and without weld reinforcement (Fig. 3(b)). So, the fatigue strength of the DMW joints can be judged as equivalent to those of similar materials welded butt joints of carbon steel.

High Mn steel is characterized by ① high work hardening, ② unclear yield shelf, ③ large tensile strength, etc. (see **Fig. 4**). Usually, high Mn steel has the yield ratio of 0.4 ~ 0.5 composed against 0.6 ~ 0.8 for carbon steel. So, the strength after plasticity can be expected. However, in fatigue strength, the high Mn base metal cannot well demonstrate its advantage of high work hardening and shows little difference from the carbon steel base metal.

3.2 Comparison with fatigue design standard curves

Figure 5 shows the fatigue test results of the DMW joints in comparison with the fatigue design standard curves [4] of Fatigue Design Recommendations for Steel Structures (Japanese Society of Steel Construction, hereafter referred to as JSSC).

In this standard, the applicable grade of fatigue strength shall be D-curve (fatigue limit: $\Delta\sigma_f$ = 100 (MPa)) for the joints with weld reinforcement (WJ-1) and B-curve ($\Delta\sigma_f$=155 (MPa)) for the joints without weld reinforcement (WJ-2). There are no data in Fig.5 in which the fatigue strength of WJ-1 and WJ-2 is below the fatigue design standard curves. So, it can be judged that fatigue design of the DMW joints is possible by using conventional fatigue design standard curves based on the material of lower strength.

3.3 Consideration

As mentioned in paragraph 3.1.2, the fatigue strength of WJ-2 joints (DMW joints without weld reinforcement) is determined by the strength of the welded metal. However, WJ-2 joints seem to have sufficient strength in the weld metal from the fact that they show fatigue strengths superior to the fatigue design standard curves (JSSC, grade B).

Moreover, in WJ-2 joints, fracture may occur in the weld metal. For that reason, the hardness of the weld metal was measured. **Figure 6** shows the distribution of hardness in the weld metal. The hardness of weld metal is not much different from that of the SS400 base metal. Namely, the yield stress of the weld metal, estimated from the hardness of high Mn steel, seems to be of the same level as that of SS400 base metal. These results exactly support the consideration in paragraph 3.1.2. Significant hardening or softening is not found in the heat affected zone.

4. Conclusion

In this study, the fatigue strength of the DMW joints (high manganese non-magnetic steel / SS400 carbon steel welded joints) is investigated for applying these joints to steel structures such as the steel bridges.

The results can be summarised as follows:

(1) Dissimilar material welded butt joints of high manganese non-magnetic steel and SS400 carbon steel (DMW joints) indicate that fatigue strengths of the same level as that of similar materials welded butt joints of SS400 carbon steel are obtained.

(2) The fatigue strength of the DMW joints exceeds the corresponding fatigue design standard curves of JSSC. In the fatigue design, the DMW joints can be treated in the same way as similar material butt joints of carbon steel in which strength is lower than high Mn steel.

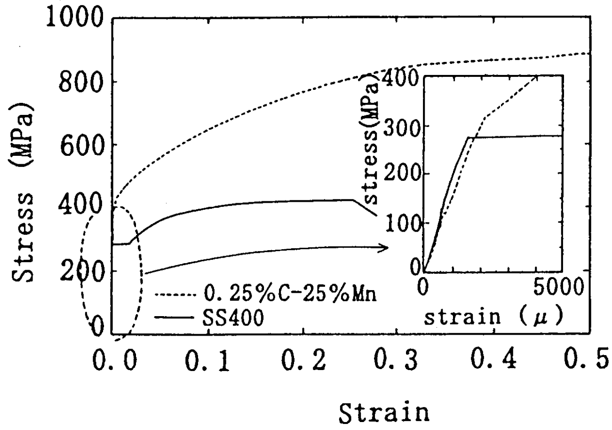


Fig.4 Stress strain curves of high Mn and carbon steel used in this study.

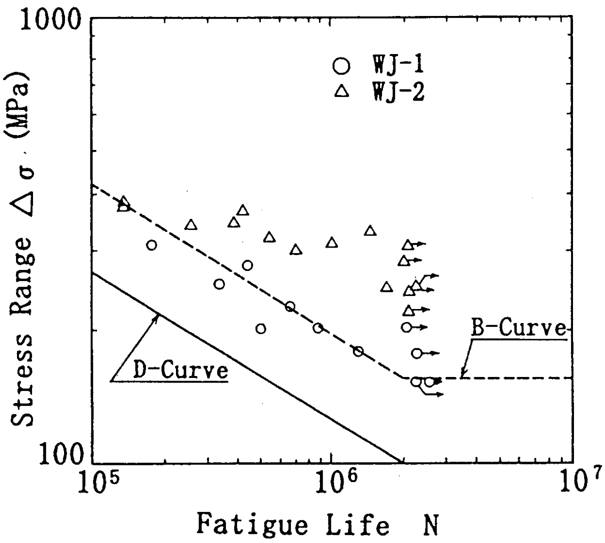


Fig.5 Comparison of fatigue test results with standard design curves.

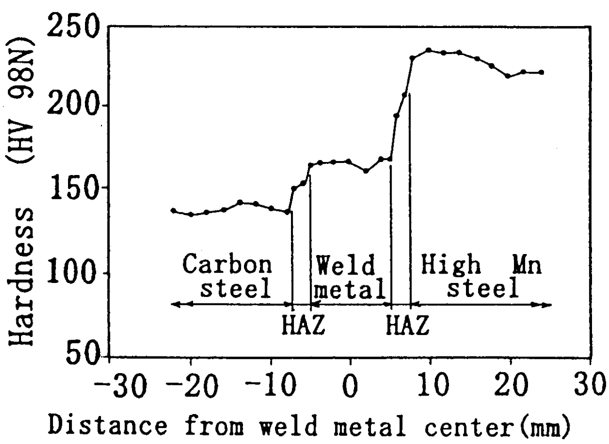


Fig.6 Hardness distribution at center of thickness.

(3) The fracture of the DMW joints without weld reinforcement may occur in the weld metal. However, it is found that the DMW joints have sufficient strength as weld metal from the fact that the fatigue strength of these joints exceeds the fatigue design standard curves (JSSC, grade B).

(4) Significant hardening or softening is not found in the heat affected zone.

Acknowledgment

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