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Repair Welding on Bridges in Service Condition†

Kohsuke HORIKAWA*, Hiroyuki SUZUKI**, Kesanori IMI***

Abstract

Fatigue Cracks have initiated in welded structures such as bridges, cranes and so on. The repair methods of these fatigue cracks have been discussed in the world.

There are some unexperienced problems in repair welding at site as the repair welding is performed under loading.

In this paper, deformation behaviors and weld crack in repair welding to structual members under loading or vibration are described.

KEY WORDS: (Repair Welding) (Deformation) (In-service Condition) (Weld Crack)

1. Introduction

In the latest days, many cases on fatigue cracks in welded structures such as steel bridge, crane and girder have been reported and the troubleshootings have been discussed world widely.$^{1)}$

There are some unexperienced problems in repair welding of steel bridge in service condition, such that

(1) static load by dead load of bridge and live load by passing vehicles are applied,
(2) complicated vibration occurs due to actual traffic and
(3) worse workability because of restraint by weather and work space which are completely different from problems in manufacturing.

Especially, the above-said problems (1) and (2) may be an important key-point when determining the actual repair procedure. Thus, quantitative analysis regarding those problems are required; as for problem (1),

(a) Probability to cause large deformation by welding to members where constant or variable load is applied.
(b) Allowable scope of repair work to carry out welding without large deformation.

and as for problem (2),

(c) Influence of vibration on weld metal – occurrence of weld crack, change of microstructure, mechanical property, etc. –

Accordingly, urgent solution of these problems in repair welding of steel bridge at site or set-up and quantitative analysis for site repairing standards have been eagerly desired.

2. Experimental Procedure

2.1 Welding under constant load

Fig. 1 shows outline of test procedure

[Tested material and test piece]

A test piece is made of SS41 and 6 mm thick, 200 mm width, 750 mm length in size, having a groove of 5 mm width and 2 mm depth in its weld section. A configuration of test piece is shown in **Fig. 2**. Chemical composition and mechanical properties of the tested material are given in **Table 1**.

[Test conditions]

A list of test conditions is given in **Table 2**.

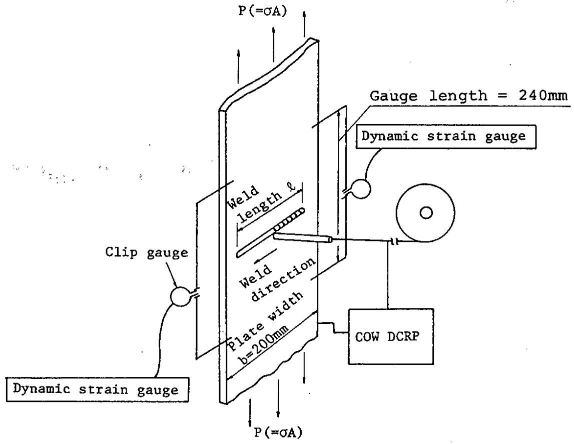

Fig. 1 Outline of test procedure ··· (I)

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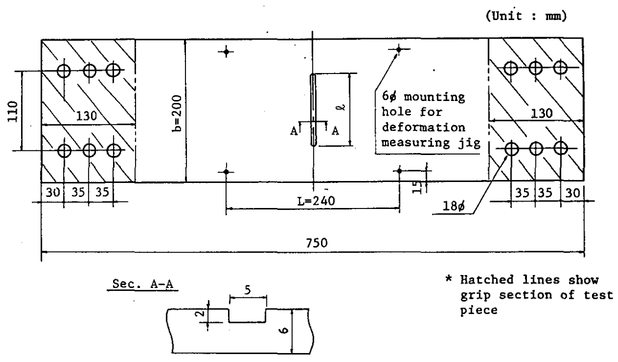


* Hatched lines show grip section of test piece

Fig. 2 Configuration of test piece

Table 1 Chemical composition and mechanical properties of tested material

	Chemical composition (wt.%)					Mechanical properties		
	C	Si	Mn	P	S	Y.P. (MPa)	T.S. (MPa)	Eℓ (%) (GL=200mm)
Material tested	0.16	0.01	0.48	0.012	0.014	333	471	28

Table 2 Test conditions

Test piece symbol	Load applied (Ton)	Weld length ℓ (mm)	Welding condition			Heat input (J/cm)	Remarks
			Curent(A)	Voltage(V)	Speed(min)		
Q1-0	0	200	200	26	30	10,400	
Q1-1	16.8	10	"	"	"	"	
Q1-2	"	50	"	"	"	"	
Q1-3	"	100	"	"	"	"	
Q1-4	"	150	"	"	"	"	
Q1-5	"	200	"	"	"	"	
Q1-6	"	200	"	"	"	"	No groove
Q2-0	0	200	170	25	15	17,000	
Q2-1	16.8	10	"	"	"	"	
Q2-2	"	50	"	"	"	"	
Q2-3	"	100	"	"	"	"	
Q2-4	"	150	"	"	"	"	
Q2-5	"	200	"	"	"	"	
Q2-6	"	200	"	"	"	"	No groove

1) Electrohydraulic type servo fatigue testing machine of max. 20 TONS was employed. Applied load was 16.8 TONS (6^t x 200^b x 14 kg/mm^2 = 16.8 TONS) to bring about allowable stress in plate.
2) Welding was performed by CO_2 gas shielded automatic welder which might give deep penetration in a horizontal posture, in order to make a temperature of overall weld section constant and to be free from temperature difference through thickness. On-the-market welding wire of mild steel, 1.2 mmϕ in size was used.

Welding conditions were determined from a preliminary welding, as follows:
(1) Good penetration and bead appearance which may be optimum for COW, i.e. heat input Q_1 = 10,400 J/cm, velocity V_1 = 30 cm/min, and
(2) Half speed of welding in (1) and increased heat input, i.e. Q_2 = 17,000 J/cm, V_2 = 15 cm/min.

Adding to the above said two conditions, two types in test pieces of length ℓ = 200 mm under loading; with groove and without groove were employed.

[Measurement of displacement]

As shown in Fig. 1, displacement was measured by clip gauge in a distance of 240 mm between marked points on each other side of weld section.

2.2 Welding under vibration

Outline of test procedure is shown in **Fig. 3**.

[Tested material and test piece]

Chemical composition and mechanical properties of a tested material are give in **Table 3**. A test piece was conformed to JIS Z 3157 "U-type restraint crack test piece", showing its configuration in **Fig. 4**.

[Test conditions]

Test conditions are given in **Table 4**.

1) Frequency and range of displacement are shown in Table 4. They were selected from the actual measured data$^{2)}$ in Hanshin Highway Corporation and a capacity of testing machine (max. 30 Hz). Vibration direction

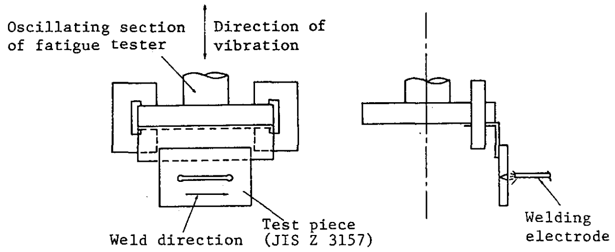


Fig. 3 Outline of test procedure ··· (II)

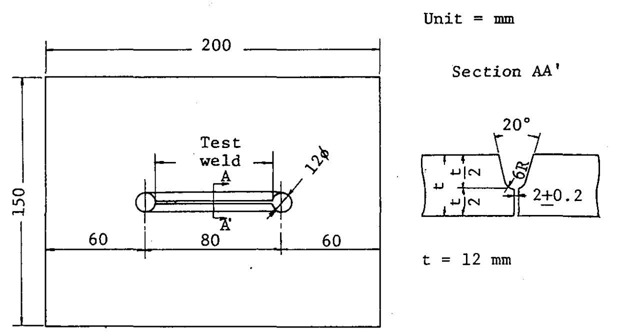


Fig. 4 Configuration of test piece

Table 3 Chemical composition and mechanical properties of tested material

	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Y.P. (MPa)	T.S. (MPa)	Eℓ (%) (GL=50mm)
plate tested	0.12	0.01	0.32	0.013	0.015	314	460	35.6

Table 4 Test conditions
(Numerical values show number of test pieces)

Vibration condition		Welding electrodes used			
Frequency	Range	D4301 (ⓈG-200)	D4316 (Ⓢ-16)	D5016 (ⓈL-55)	D4316 (ⓈL-43LH)
Hz 0	mm 0	3	3	3	3
0.3	1.0	"	"	"	"
3.0	0.6	"	"	"	"
30.0	0.02	"	"	"	"

was at right angle to weld line (See Fig. 3). Vibration was applied to the test piece during and for five minutes after welding. Only vibration added.

2) Shielded Metal Arc Welding (SMAW) was employed under heat input Q = 17,000 J/cm (170A x 25V x 15 cm/min). In this experiment a welding posture was horizontal, normally flat in crack test, because of testing machine's position to apply vibration.
Moreover, to check for difference due to weld material, the following four types of welding electrodes were employed.
   (1) Ilmenite type rod for a class of 392MPa (G-200) as widely used
   (2) Low hydrogen type rod for a class of 392MPa (16) which is superior in crack resistance
   (3) Low hydrogen type rod for a class of 490MPa (L-55) considering the repair for a class of 490MPa materials
   (4) Super low hydrogen type rod for a class of 392MPa (L-43LH)

3) For valuation of crack, macrostructures in 5 sections of weld metal after 48 hours or more from completion of welding was picked up and checked for sectional crack ratio.

$$\text{Sectional crack ratio} = \frac{Hc}{H} \times 100\%$$

where, H : Minimum weld thickness of test bead
Hc: Height of root crack

4) After crack test, microstructure in section was checked.

3. Experimental Results and Discussions

3.1 Welding under constant load

1) Deformation behavior

Fig. 5 ~ 7 show deformation behaviors of test plate after starting weld.

(1) In case weld length (ℓ) for plate width (b) is short ($\ell/b \leq 0.5$), both welding start side (herein after referred to as side S) and welding end side (herein after referred to as side E) change in a similar pattern.

(2) Where $\ell/b \geq 0.75$, the difference between sides S and E becomes greater, resulting that deformation on side E becomes two or more times larger than on side S , in maximum deformation.
Further, both sides S and E have typical de-

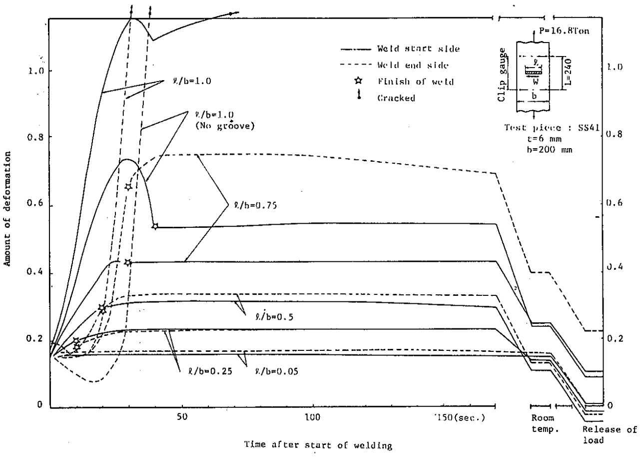


Fig. 5 Deformation behavior during welding (Q = 10,400 J/cm)

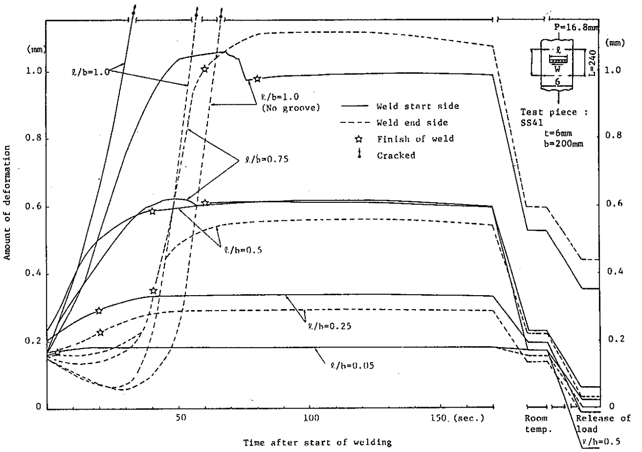


Fig. 6 Deformation behavior during welding (Q = 17,000 J/cm)

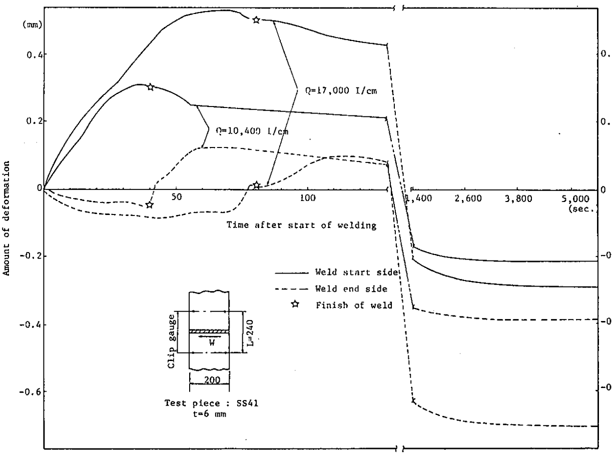


Fig. 7 Deformation behavior during welding (Without loading)

formation pattern. Deformation on side S enlarges rapidly upon weld starting, having its peak just before completion of welding. While, deformation on side E , once having shrinkage deformation, enlarges rapidly when welding comes just around the center of plate width, and even after cooling down to room temperature, elongating deformation still remains.

(3) The larger becomes ℓ/b, the more becomes elongation during welding. The higher is the weld heat input, the more is deformation in comparison to Fig. 5 and 6.
The result shows the fact that weld heat input rather than weld speed gives greater influence on deformation.

(4) In the test piece welded in overall width without load, deformation behavior, as shown in Fig. 7, is such that elongation is caused gradually on side S upon starting welding and maximum elongation is obtained just before completion of welding. Shrinkage deformation on side E during welding turns to elongate at the same time of weld completion and reaches maximum elongation in 20~30 seconds. Then, accompanied with cooling welds on both sides S and E begin to shrink, causing residual shrinkage deformation of 0.31 mm (Q = 10,400 J/cm), 0.5 mm (Q = 17,000 J/cm) on average at room temperature.
The values show good agreement to theoretical values[3] (0.32 mm, 0.53 mm respectively) calculated by assuming heat efficiency as 75%.

Fig. 8, **9** and **10** show "Maximum deformation during welding", "Residual deformation after cooling to room temperature" and "Residual deformation after unloading" respectively given by ℓ/b. The Figs. exhibit the fact that deformation increases rapidly when ℓ/b exceeds 0.75 in each case. The Figs. also show the larger heat input causes larger deformation and residual deformation.

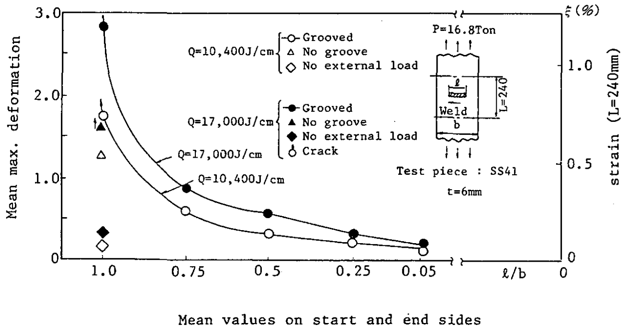


Fig. 8 Max. deformation of welds

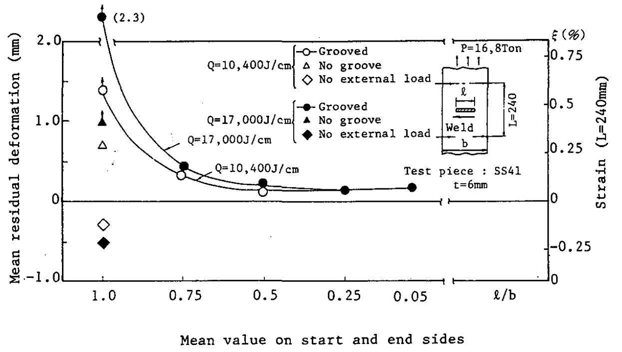


Fig. 9 Residual deformation after cooling to room temperature

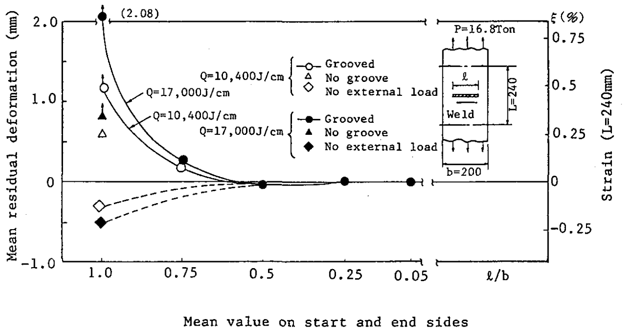


Fig. 10 Residual deformation after unloading

From the above-said results of deformation behavior, in practical welding optimum weld length per plate width may be $\ell/b \leq 0.5$, if the conditions are similar with those in this experiment.

2) Weld crack

For the test pieces which have had edge preparation and ℓ/b = 1.0, weld cracks over 70 mm in length appeared on the side E regardless of heat input. Crack of approx. 20 mm in length appeared also on the Q2-6 test piece (no edge preparation, Q = 17,000 J/cm).

In every cases, the location of cracks was at the center of bead, and the cracks were longitudinal ones penetrating through the thickness. All of the cracks occurred just before finish of weld. These may be considered as ductile fracture in high temperature. **Fig. 11** shows the state of cracks described from the RT film. **Fig. 12** represents change in temperature after start of weld. As can be seen from the figure, the temperature at the side S is comparatively high, approx. 350°C even after welding has been finished.

On the other hand, the temperature at the side E is considered the same level as the peak temperature shown in the figure. Consequently, it is considered that fracture occurred on the side E having high temperature because the entire section of welds was unable to support external load.

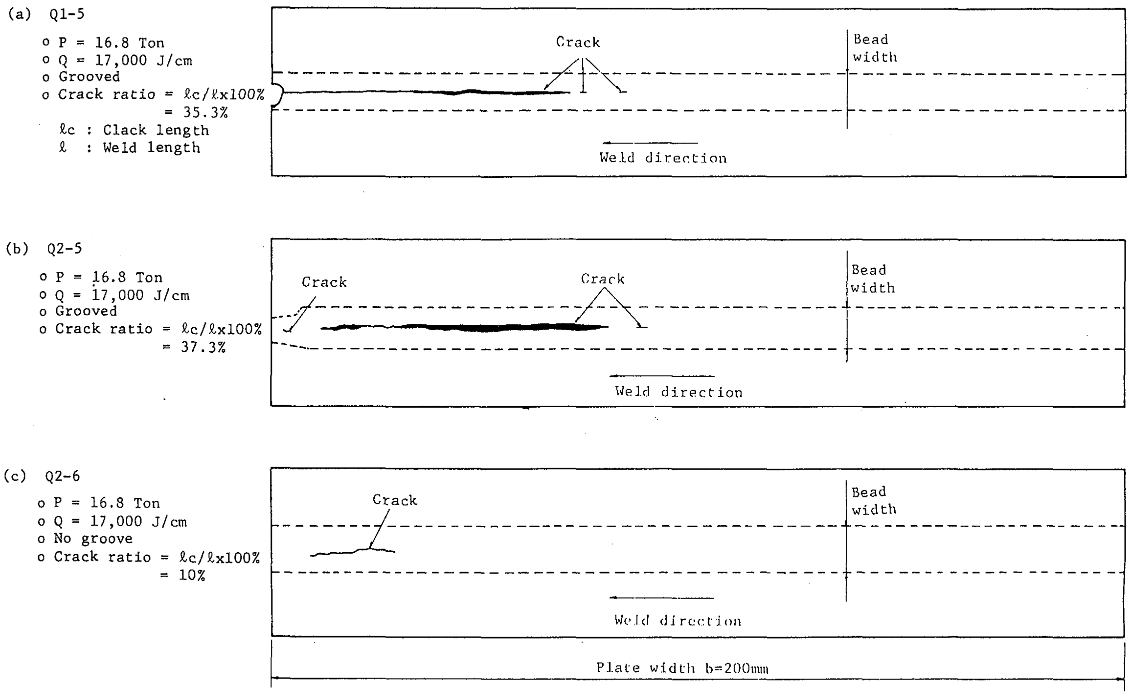


Fig. 11 State of weld cracks (sketch from RT films)

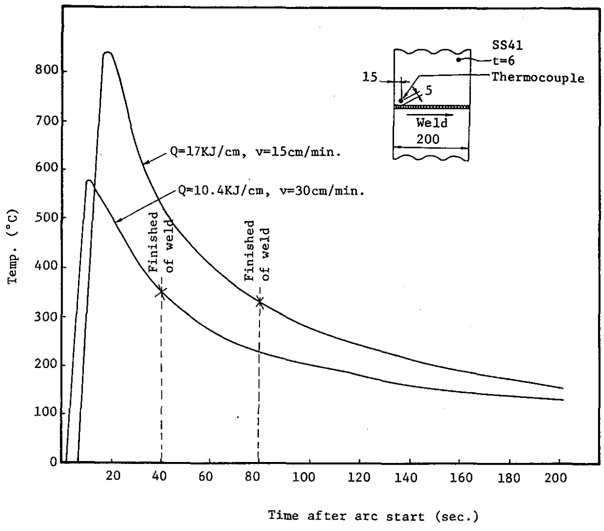


Fig. 12 Temp. change after start of weld

3) Repair weld work under the condition subject to tensile load

Assuming that practical welding work is performed under the same condition as that of the experiment, weld cracks will generate with $\ell/b = 1$ as shown in Figs. 8 and 9. It is therefore considered that it is impossible to make repair weld of the entire section of a member almost at the same time under the condition mentioned above. Residual deformation hardly generates with $\ell/b \leqq 0.5$, and if the actual weld is made under the same condition as that of the experiment, repair weld may be possible by setting the range of welding to $\ell/b \leqq 0.5$. In an actual bridge structure, it is hardly to consider the case of $\ell/b = 1$, that is, fracture occurs in the entire sections of a member, and in usual case, the value may be very low. Therefore, most of cracks may be repaired with a guide line of $\ell/b \leqq 0.5$.

This guide line ($\ell/b \leq 0.5$) varies as a matter of course depending upon thickness and width of member to be welded, and external load (applied stress). However, in the case of increased thickness and width of plates, and decreased external load, the guide line is considered as conservative side than the present experiment. Therefore, under such condition, this guide line may be usable.

ℓ/b has been discussed in this paper, which means a ratio of a deficit portion in the load withstanding section to total sectional area in weld in the case where static tensile stress is loaded on a flat plate.

However, it is usual that actual structures have three-dimensional sections, and various applied stresses such as bending stress, etc. may be imposed on it. Whether or not the present guide line is applicable to the above-mentioned case or completely different guide line is needed will be studied in future.

3.2 Welding under vibration

1) Effect on weld crack

Fig. 13 shows the results of sectional crack ratio. As

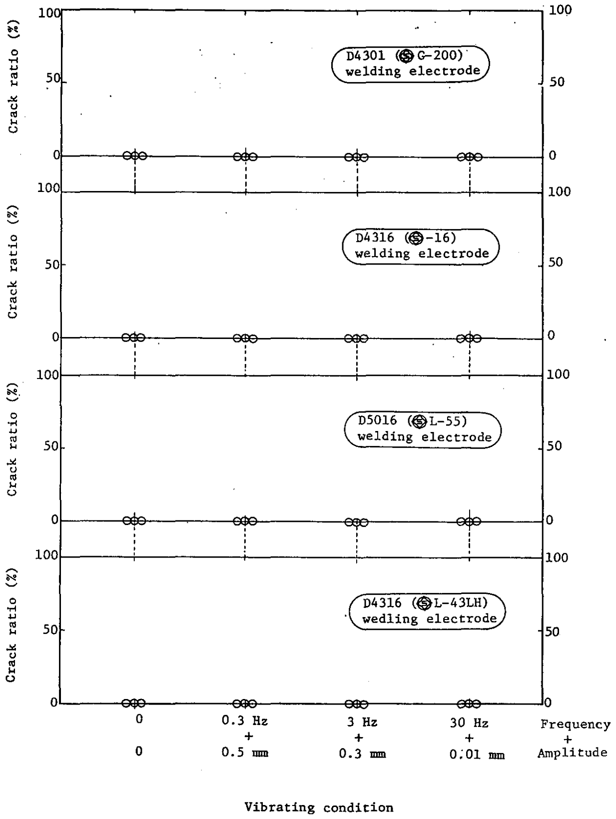


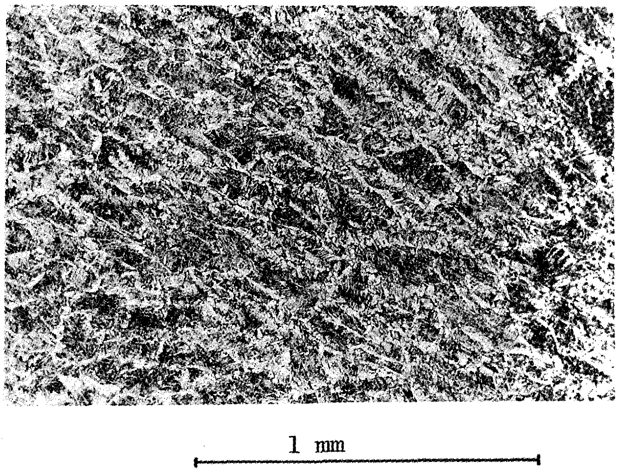
Fig. 13 Results of weld crack test under the condition of vibrations

can be seen in the Fig., no crack was recognized in each case, and no difference due to change in vibrating conditions and types of welding electrode was found.

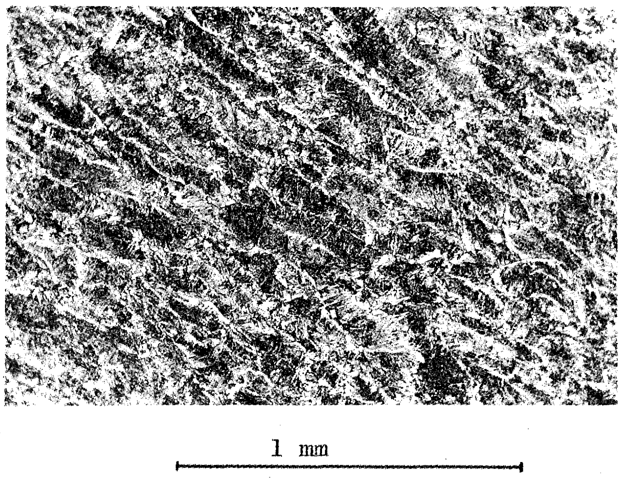
2) Effect on weld metal structure

Typical microstructure is shown in **Fig. 14**. In any of vibrating conditions no difference was recognized. Weld metal, after being etched with super-saturated with picric acid, was observed continuously from the weld bond in order to examine the state of development of the columnar structure. Although it can not be clearly pointed out because of the structure after transition, the columnar structure has been developed in almost linear form to the center of bead from the weld bond irrespective of vibrating conditions. There was no tendency in the direction of development of the columnar structure to be changed due to the effect of vibration. If such change should occur, it causes the weld metal structure to be improved and is considered that advantageous effects such as improved toughness, etc. may be produced.

3) Judging from 1) and 2), it can be said that there is no effect on microstructure of welds or weld crack under the vibration to such an extent.



(a) Welding Without Vibration



(b) Welding Under the Vibration Condition of 30 Hz x 0.02 mm

Fig. 14 Typical Appearance of Microstructure (Electrode; D4316)

4. Conclusions and Problems in Future

Tests were made on (1) weld test of flat plates under a static load, and (2) weld crack under vibration for the purpose of obtaining a work guide line for the repair welding on welded structures such as bridges, etc. in service condition, and the following results were obtained.

1) Weld under a static load
   (1) Comparing the deformation behaviors recorded continuously after start of weld, it has become clear that characteristic behaviors occur respectively depending upon the ratio of weld length to entire width of a plate.
   (2) Amounts of deformation during weld or after weld were arranged with the ratio (ℓ/b) of weld length to plate width, and examined. As a result of the examination, the following guide lines were obtained within the range of the conditions for the

experiment.

(a) When $\ell/b = 1$, that is, the entire section of a plate is welded almost simultaneously, weld cracks or large deformation will occur, and weld work in this manner is not applicable, and

(b) With $\ell/b \leqq 0.5$, residual deformation hardly occurs after weld and weld work under the condition of $\ell/b = 0.5$ is applicable.

2) Welding under vibration

(1) Welding were made under various vibration conditions using small-size crack test pieces, and crack tests were made. The crack ratio was 0% under any conditions.

(2) The results of observation of microstructure of crack test pieces have shown that vibration does not have effect on the weld metal structure.

(3) From the above-mentioned (1) and (2), vibration generated in an actual structure is considered to have no effect on weld crack, weld metal structure as for the range of condition under which this experiment was made.

[Problems in future]

The present experiment was made for obtaining basic information about a work guide line for repair welding on welded structures in service condition.

As for welding under vibration, it seems that there will be almost no problem in actual execution of weld work in consideration of the results of experiment conducted by Hanshin Highway Corporation[2),4)].

As for welding under loading, however, additional studies are considered necessary for applying the present results to steel members actually in service. Because an actual structure in service is subject to not only tensile stress but other stresses such as compression, bending, etc..

Especially, buckling is the most concern on the members subject to compression load. Therefore further study should be made on various cases for these stresses.

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