EFFECT OF UIT ON FATIGUE STRENGTH OF WEB-GUSSET WELDED JOINTS CONSIDERING SERVICE CONDITION OF STEEL STRUCTURES

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ABSTRACT

UIT (Ultrasonic Impact Treatment) is a method to impact on the weld toe with hard pins vibrated by ultrasonic energy, so that the improvement of the weld toe profile and the introduction of the compressive residual stress can be obtained. It is confirmed that UIT has high improving effect on fatigue strength of welded joints through many experimental researches. Those tests were conducted under low stress ratio and UIT was done in condition that specimens were not subjected to stress. When the UIT method is applied to existing structures, its effect should be verified in condition that UIT is applied under loading and fatigue tests are performed under high stress ratio. In this study, the improvement effects have been examined under such conditions.

The main results obtained here are as follows.

(1) When UIT is given under no load, the remarkable effect of UIT on fatigue strength can be obtained in low stress ratio, and the effect can not be obtained in high stress ratio.

(2) When UIT is given under no load, effect of UIT becomes remarkable as the maximum stress is low and stress range is large.

(3) A remarkable effect of UIT is obtained when UIT is given under load. Especially, fatigue strength when UIT is done under the maximum load is twice or more as that of as-welded joint.

(4) The effect of UIT on the fatigue strength is mainly derived from compressive residual stress. Improvement of fatigue strength due to the modification of weld toe shape by UIT is not re-markable.

IIW-Thesaurus keywords: Ultrasonic; Impact; Treatment; Fatigue strength, Gusset; Welded joints; Structure.

1 Introduction

In general, the fatigue strength of steel plates is considered to increase in proportion to its static strength. On the other hand, the fatigue strength of welded joints which are usually weak points in fatigue is not known to be influenced by the static strength level [1-4]. Therefore, it is necessary to improve the fatigue strength of the welded joints in order to use high strength steel efficiently.

Technology for improving fatigue strength of welded joints can be divided into different categories:

1) improving the weld toe shape to reduce the stress concentration by using grinder,
2) yielding compressive residual stress to the weld toe by using low transformation temperature welding material.

In addition, peening method can be expected above two effects. Peening is the method for giving impact repeatedly to the weld toe by a hammer or a pin, and it can give tensile plastic deformation at the weld toe and compressive residual stress in addition to smooth the weld toe profile. In the present paper, the authors carefully studied UIT (Ultrasonic Impact Treatment), considered as one of the peening methods.

As for the UIT method, metallic pins of high hardness are installed in guiding holes and excited by the ultrasonic oscillation system. And the pin moves along the axis of the oscillation system and impacts repeatedly into the weld toe. This method has already been applied to the actual structures such as upper jackets of piers for Tokyo International Airport (Haneda) D-Runway [5], crane girders [6] and so on. UIT method has features described as

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follow. Its equipment is small so that it can be carried easily, the reaction force by it and driving sound are small because of using ultrasonic energy, and it can be handled easily. Moreover, this method is considered to have capability to give large plastic deformation and high compressive residual stress at the weld toe.

Several experimental studies on the effect of UIT on the fatigue strength have been performed in the condition that UIT was done under no load and lower stress almost equal to 0 [6-11]. In case of steel plates without residual stresses, its fatigue strength decreases with the increase of the stress ratio (mean stress). On the other hand, the fatigue strength of welded joints with high tensile residual stress is almost constant regardless of the stress ratio. One factor for improving the fatigue strength by UIT is the decrease in a local stress ratio at the weld toe because of the introduction of the compressive residual stresses. This fatigue strength improvement mechanism has been tested and explained by the modified Goodman diagram or the crack propagation analysis considering the residual stress state influenced by loading [11-14]. Therefore, the influence of the stress ratio on fatigue strength of welded joints with weld toe treated by UIT must be made clear. That is, the welded joints in an actual structures are often subjected to cyclic stress with high lower stress (high stress ratio) because of dead loads, so the effect of UIT must be confirmed in such conditions. Moreover, it is also necessary to make clear the effect when UIT is done under load in the case that it is applied to the existing steel structures.

In this study, fatigue tests and 3D-FE analyses on out-of-plane gusset welded joints are performed to enhance the knowledge of the influence of the static stress level when applying UIT and the stress ratio on fatigue strength.

2 Test Methods

2.1 Specimens

High strength steel of 12 mm thickness for bridges SBHS500 (JIS G 3140) were used for out-of-plane gusset welded joint specimens. Here, two kinds of steel (steel A and B) were used and their mechanical properties and chemical compositions are shown in Table 1. Configuration and dimensions of the specimen is shown in Figure 1. Semi-automatic CO_2 arc welding was used for connecting main plates and gusset plates. Welding consists of the fillet weld and the groove weld. Steel A was used for fillet welded specimens and steel B was used for groove welded specimens. Welding materials are YFW-C60FR(AWS E81T1-N) of flux core-type for high strength steel specified in Japan Industrial Standard (JIS Z 3313).

The fillet welds and the groove weld are completed by one pass and two passes, respectively. In each welding, the welding current and the voltage were set at 250 A and

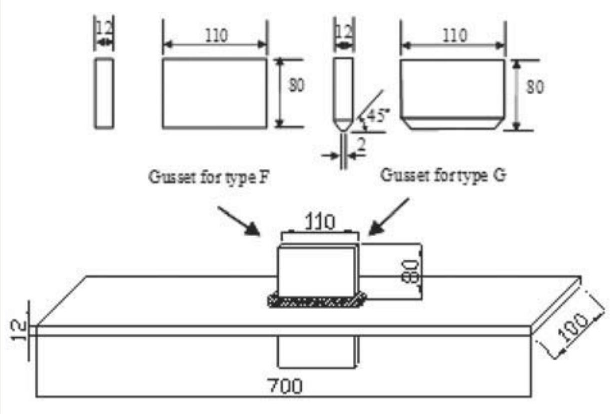

Figure 1 – Configuration and dimensions of specimen

28 V. The grooves were set on the main plate side edge of the gusset plates of G-AW and G-UIT specimens. The angle is 45 degrees and the depth is 5 mm so that the width of root face becomes 2 mm. In particular, the gusset plates for G-AW and G-UIT clamped tightly, to avoid the tilt of the plate during fillet welding.

As UIT equipment, ESONIX®27 UIS made by Applied Ultrasonics was used. The diameter of the pin used for the treatment was 3 mm. Specimens are roughly divided into 4, they are F-AW specimens (fillet weld, as-welded), F-UIT specimens (fillet weld, UIT), G-AW specimens (groove weld, as-welded) and G-UIT specimens (groove weld, UIT). Moreover, UIT is done under no load, maximum stress and minimum stress of cyclic stresses in fatigue tests. Conditions of these UIT operations are called {1}, {2} and {3}, respectively. The appearance in which UIT is done under the load is shown in Figure 2. Here, the name of specimens is distinguished by fillet weld (F) or groove

Figure 2 – UIT operation

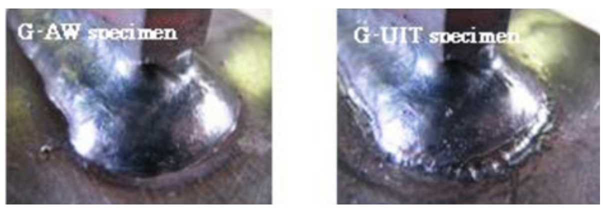

Figure 3 – Appearances of welded parts

Table 1 – Mechanical properties and chemical compositions of the steel used

Steel	Mechanical properties			Chemical compositions (%)						
	Yield stress	Tensile strength	Elongation	C	Si	Mn	P	S	P_{CM}	CE (IIW)
	N/mm²	N/mm²	%	x100	x100	x100	x1000	x1000	x100	x100
A	575	665	33	10	23	152	8	2	19	35
B	572	661	27	10	22	153	6	2	20	35

Table 2 – Test conditions

Name of specimen	Stress level at UIT operation	Test conditions
F-AW	–	R=0 , R=0.5
G-AW	–	R=0 , R=0.5
F-UIT{1}	0	R=0 , R=0.5
G-UIT{1}	0	R=0 , R=0.5 maximum stress constant (208, 268, 300, 352, 400 N/mm²)
F-UIT{2}	Maximum stress	R=0.5
G-UIT{2}	Maximum stress	R=0.5
F-UIT{3}	Minimum stress	R=0.5
G-UIT{3}	Minimum stress	R=0.5

weld (G), as-welded (AW) or operations by UIT (UIT), and the stress conditions in UIT operations ({1}, {2} and {3}) as shown in Table 2.

Examples of appearances of G-AW specimens and G-UIT specimens are shown in Figure 3. The weld leg length of boxing welds and radius of curvature and flank angle at the weld toe on the main plate side were measured. The results are shown in Table 3. The weld shape and size of F-specimens are almost the same as those of G-specimens.

Residual stress distributions measured in F-AW specimen and F-UIT{1} specimen are shown in Figure 4. This measurement was done using X-ray diffraction method (sin2 φ method). Positions of measurement points are 5 mm away from the weld toe and 10mm pitch in the lateral direction. Moreover, the position 2, 5 and 8 mm away from the weld toe were also measured in the longitudinal direction along

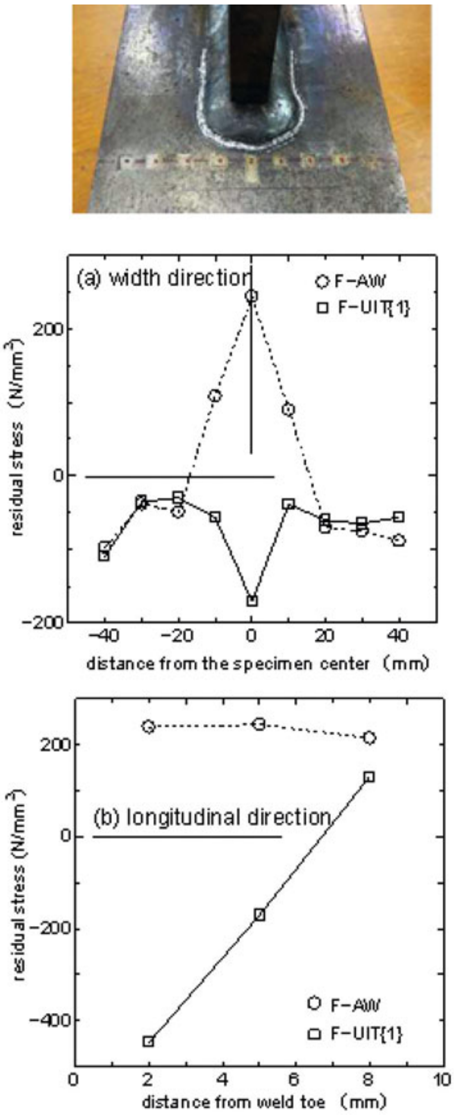

Figure 4 – Residual stress distribution

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Table 3 – Shape and size of welds

Specimen	The number of specimens	The number of samples	Average weld leg length (mm)		Weld toe radius (mm)		Flank angle (deg.)	
			Main plate side	Gusset plate side	Main plate side	Standard deviation	Main plate side	Standard deviation
F-AW	7	200	10.8	8.2	0.8	0.49	139	6.9
G-AW	14	1120	10.7	8.8	0.5	0.25	138	5.9
F-UIT	10	200	12.5	8.2	2.1	0.30	139	2.9
G-UIT	44	800	11.6	9.3	1.7	0.34	147	3.2

the centre of the specimen. The residual stresses along the line 5 mm away from the weld toe shown in Figure 4a) has changed greatly by doing UIT in the area within 20 mm away from the specimen centre. For example, the value of residual stress at the centre is about 220 N/mm^2 (tension) for the F-AW specimen, and is about 180 N/mm^2 (compression) for the F-UIT{1} specimen. Residual stresses shown in Figure 4b) which indicates those in the longitudinal direction are almost constant in the F-AW specimen regardless of location. However, compressive residual stress on the F-UIT{1} specimen becomes high as the location is close to the weld toe. From the distribution, it is expected that the value of compressive residual stress at the weld toe is almost equal to the yield stress of the steel used.

2.2 Experimental Work

The fatigue tests were performed under tensile axial constant amplitude loading with an electrohydraulic servo type machine with the dynamic capacity of 500 kN. These tests are in the condition of stress ratio R = 0 or R = 0.5. In addition, the G-UIT{1} specimens in which UIT was done under no load were fatigue tested in the condition that upper stress is constant (208, 268, 300, 352, 400 N/mm^2) and stress range is varied. The fatigue test conditions of each type of specimen are shown in Table 2. The stress wave form used for the fatigue tests is a sine wave, and the frequency is 6 to 12 Hz.

3 Fatigue Test Results

3.1 As-welded Specimen (F-AW and G-AW specimens)

The fatigue test results of the F-AW specimens and the G-AW specimens are shown in Figure 5. The mark in the figure was distinguished according to fillet weld or

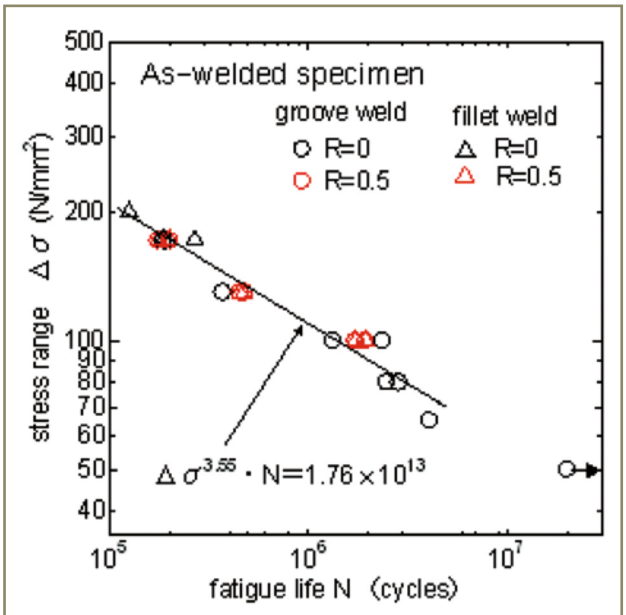

Figure 5 – Fatigue test results of as-welded specimens

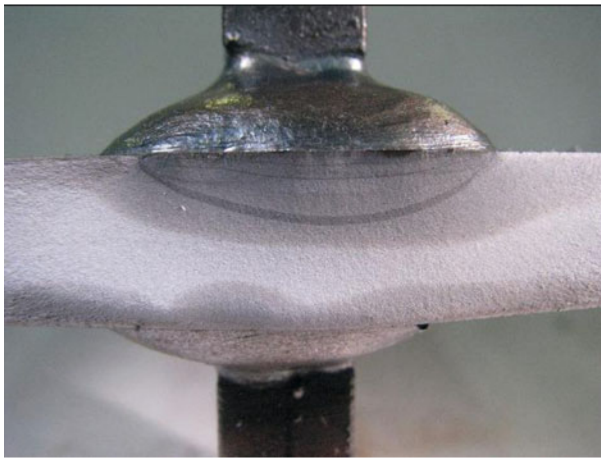

Figure 6 – Fatigue failure surface of as-welded specimen

groove weld, and stress ratio R. The fatigue strength of the F-AW specimens and the G-AW specimens is almost the same as each other. Moreover, fatigue strength of each type of specimen does not depend on stress ratio (R = 0, R = 0.5). The reason of these facts is considered to be derived from that weld geometry of F-AW specimen and G-AW specimen is similar and high tensile residual stress exist at the weld toe of fatigue crack origin. The mean value of the assessed fatigue life is also shown in Figure 5. This regression line represents a fifty percent probability of survival Hereafter, the effect of UIT on the fatigue strength improvement will be examined based on this regression line.

All the fatigue cracks of the F-AW specimens and the G-AW specimens were initiated and propagated from the weld toes. An example of these fatigue failure surfaces is shown in Figure 6. On this specimen, the beachmark test in which stress range was reduced by half with the upper limit stress being constant in each prescribed number of stress cycles was done. Multiple fatigue cracks emanating from the weld toe are observed, and they have propagated as semi-elliptical cracks before they collapse into one single crack.

3.2 UIT{1} Specimens (R=0)

Fatigue test results of specimens which were operated by UIT under no load and tested under stress ratio R = 0 are shown in Figure 7 The regression $\Delta\sigma$-N line for as-welded joints shown in Figure 5 is also indicated in Figure 7. The assessed fatigue life of UIT-specimens is at a finite life stress range of about 180 N/mm^2, five to ten times higher compared to test results of untreated as-welded stiffeners. In addition, as for the G-UIT{1} specimens, fatigue failure did not occur, nevertheless cyclic stress was applied up to three million or six million, therefor fatigue lives of the G-UIT{1} specimens are 15 times or more compared to those of as-welded specimens.

Fatigue crack initiating point of F-UIT{1} specimens was not the weld toe and it was the weld root as shown in Figure 8a). It is thought that this is because fatigue strength in the case of the toe failure becomes high by

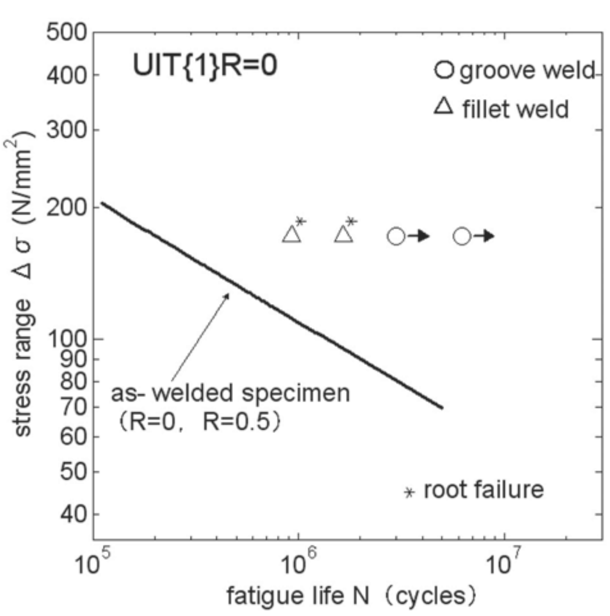

Figure 7 – Fatigue test results of UIT{1} R = 0 specimens

UIT, and fatigue strength in the case of root failure is comparably low. The fatigue crack initiated from the weld root should be prevented because it is difficult to detect the crack until it propagates to the surface.

3.3 UIT{1} Specimens (R = 0.5)

Fatigue test results of specimens which were operated by UIT under no load and tested under stress ratio R = 0.5 are shown in Figure 9. The fatigue strength of G-UIT{1} specimens and F-UIT{1} specimens is almost the same, and these results are different from the fact indicated in previous section. All the fatigue crack origins were weld toes operated by UIT regardless of specimen type. An example of the fatigue failure surface of F-UIT{1} specimens is shown in Figure 8b). This fact suggests that fatigue strength in the case of toe failure is low compared with that in the case of root failure when stress ratio is high such as R = 0.5.

Fatigue strength of F-UIT{1} and G-UIT{1} specimens are almost the same and both are similar to that of as-welded specimens. In Figure 9, $\Delta\sigma$-N regression line for F-UIT{1} and G-UIT{1} specimens tested under R = 0.5 is also indicated. The mean fatigue strength at two million cycles obtained from the line is 93 N/mm², and the improvement level of fatigue strength is only 3 % because the strength of as-welded specimens is 90 N/mm². Thus, effects of UIT on the fatigue strength are little. It is thought that this is because the effect of the compressive residual stress by UIT became small under high stress ratio. However, G-UIT{1} specimen tested under stress range equal to 100 N/mm² did not fail, nevertheless this specimen was loaded up to ~10 million stress cycles. The fact that the effect of UIT was not obtained when stress range is large and was obtained when stress range was small as mentioned above may mean that fatigue strength improvement effect of UIT depends on the maximum stress level (200 N/mm² in case of stress range equal to 100 N/mm², 400 N/mm² in case of stress range equal to 200 N/mm²) rather than stress ratio itself. In other words, it is thought that such a phenomenon was caused because the plastic strain on the tension side is created in the weld operated by UIT and the compressive residual stress introduced by UIT is partially released when the upper stress is high.

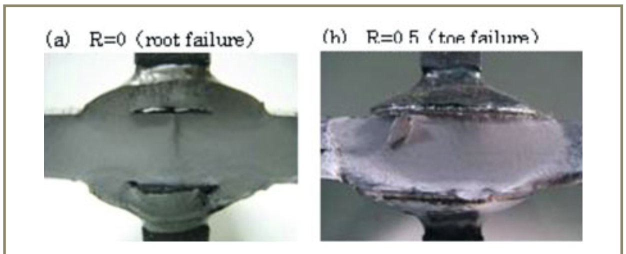

Figure 8 – Examples of fatigue failure surfaces of F-UIT{1} specimens

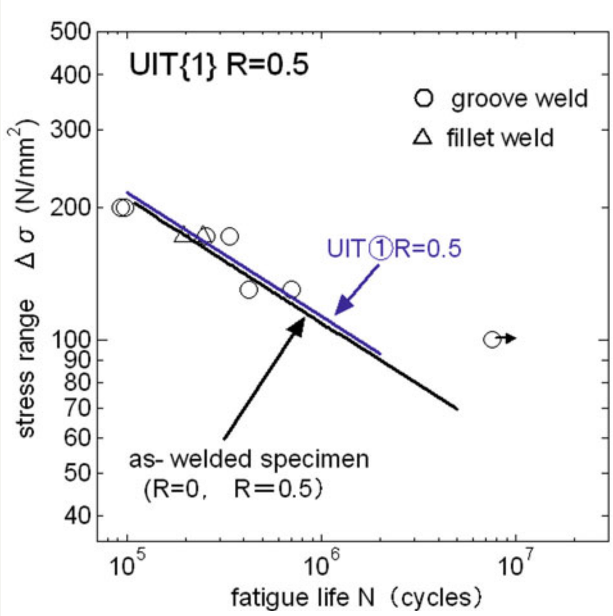

Figure 9 – Fatigue test results of UIT{1} R = 0.5 specimens

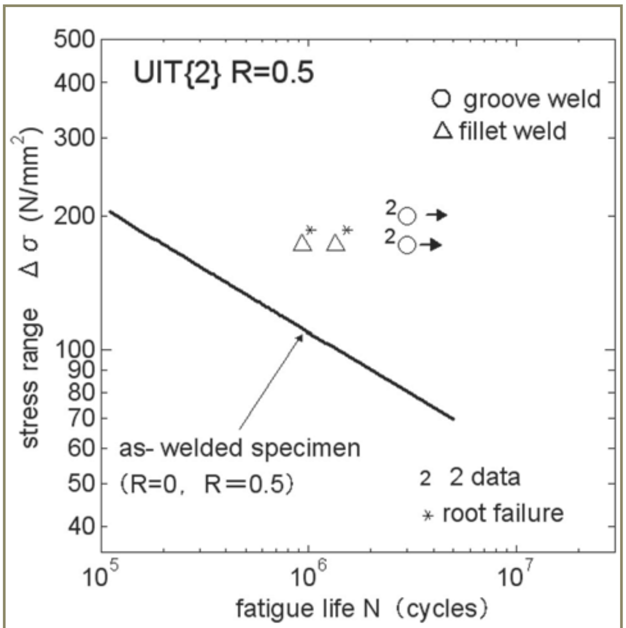

Figure 10 – Fatigue test results of UIT{2} R = 0.5 specimens

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3.4 UIT{2} specimens (R = 0.5)

Fatigue test results of F-UIT{2} and G-UIT{2} specimens which were operated by UIT under the maximum stress in the fatigue tests and tested under stress ratio R = 0.5 are shown in Figure 10. Fatigue crack origins of F-UIT{2} specimens were all the weld roots. This results is the same as the result of F-UIT{1} specimens operated by UIT under no load and tested with R=0. When F-UIT{1} specimens were fatigue tested with R = 0.5, fatigue crack origins were weld toes. These facts suggest that high fatigue strength improvement was surely obtained by UIT when it is operated under the maximum stress.

The G-UIT{2} specimens were fatigue tested under the conditions of $\Delta\sigma = 200$ N/mm^2 (R = 0.5) and $\Delta\sigma = 180$ N/mm^2 (R = 0.5). In these cases, fatigue crack was not observed when the number of stress cycles reached 3 million. This fatigue strength is twice or more as high as that of as-welded specimens and UIT{1} specimens (R = 0.5). This result indicates that high improvement effect by UIT on fatigue strength can also be obtained under the condition of high stress ratio when UIT is operated under loading, that is to say, applied to existing structures.

3.5 UIT{3} specimens (R = 0.5)

Fatigue test results of F-UIT{3} and G-UIT{3} specimens which were operated by UIT under the minimum stress in the fatigue tests and tested under stress ratio R = 0.5 are shown in Figure 11. Fatigue failure of F-UIT{3} specimens occurred from weld root, and this result is same as that of and F-UIT{2} (R = 0.5) and F-UIT{1} (R = 0) specimens. These specimens were fatigue tested under $\Delta\sigma$ = 172 N/mm^2, and the difference of those fatigue lives is small. This fact suggests that the fatigue strength in the case of root failure does not depend on stress level in UIT operation and the stress ratio so much.

The fatigue strength of G-UIT{3} specimens of which fatigue failure originated from the toes is lower than that of G-UIT{2} R = 0.5 specimens, but higher than that of G-UIT{1} R = 0.5 specimens. Thus, the stress level when UIT is operated gives a big influence on the effect of the fatigue strength improvement.

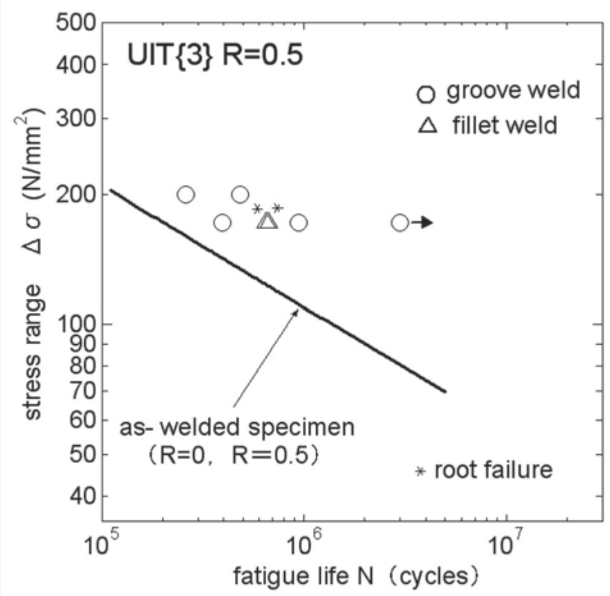

Figure 11 – Fatigue test results of UIT{3} R = 0.5 specimens

3.6 G-UIT{1} Specimens (influence of the maximum stress)

In section (3), it was described that the effect of the compressive residual stress by UIT was not observed when UIT was done under no load and the fatigue tests were done under the stress ratio R = 0.5, because the effect of the compressive residual stress might disappear when the upper stress was high. When there is no residual stress, the stress range in a tensile region controls the fatigue life, and the stress range in a compressive region does not contribute to fatigue damage [4, 15]. The effect of compressive residual stress by UIT on the fatigue strength could be derived from such a mechanism. This idea is shown in Figure 12 graphically. That is, all the stress range contributes to the fatigue failure in a region where the effect of compressive residual stress doesn't appear, but compressive residual stress effect exists in a region where the stress range exceeds the limit of compressive residual stress effect as shown in Figure 12 b). Therefore, the effect of UIT is remarkable as the maximum stress is low and stress range is large. In addition, the influence of the stress ratio on fatigue strength of as-welded joints is not prone to appear as shown in Figure 12 c).

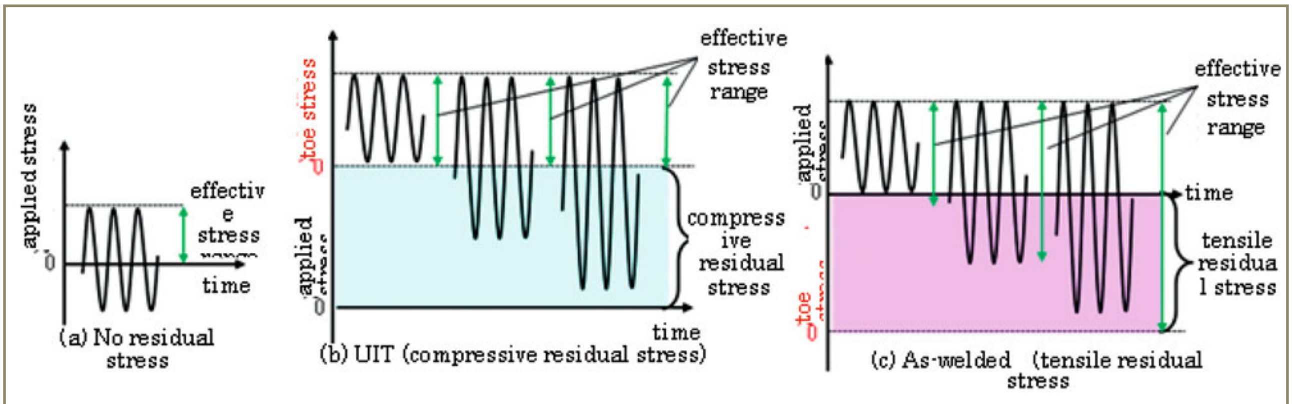

Figure 12 – Fatigue strength improvement by compressive residual stress

Figure 13 shows fatigue test results of specimens which were done by UIT under no load and tested under the maximum stress being set at constant. When the maximum stress is 400 or 352 N/mm2, the effect of UIT on fatigue strength is not observed in all the stress ranges. However, when the maximum stress is 208 N/mm^2, remarkable improvement of the fatigue strength is apparent. When the maximum stress is 300 or 268 N/mm^2, the effect is not recognized in a region of small stress range ($\Delta\sigma = 100, 130$ N/mm^2), but fatigue lives are improved in a region of large stress range ($\Delta\sigma = 172, 200$ N/mm^2) compared with those of AW specimens. These results coincide with the tendency of above mentioned fatigue strength improvement mechanism by UIT. If this idea is correct, fatigue life corresponding to stress range of 172 N/mm^2 must be consistent with that of 200 N/mm^2, but they are not similar. This fact may mean that the effect of compressive residual stress does not only depend on the maximum stress but also on the minimum stress. It is thought that further considerations are necessary to show the fatigue strength improvement mechanism by the compressive residual stress quantitatively.

4 Stress Analysis

4.1 Numerical Model and Method

In order to examine the influence of the weld toe shape improvement by UIT on fatigue strength, the elastic 3D FE stress analyses were performed on the specimens used here. The stress analyses were done on 1/8 models because of the symmetry configuration of the specimens shown in Figure 1. FEMAP was used as a pre-post tool and CAFEM was used as an analysis tool. In these analyses, the Young's modulus was set at 2.06 × 105 N/mm^2, and Poisson ratio was set at 0.3. Numerical models consist of the following three series.

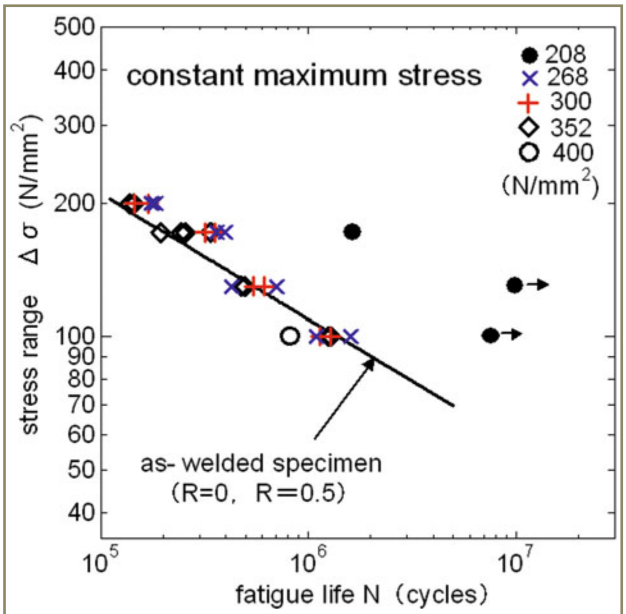

Figure 13 – Results of fatigue tests with constant maximum stress

The series I model is AW model and UIT model which were based on the measured results of the weld leg length, the toe radius and toe flank angle shown in Table 3. The toe radius of the AW model is assumed to be 0.7 mm and the toe radius of the UIT model is assumed to be 1.9 mm. The element size near the weld toe is set at 0.1 mm. Figure 14 shows the finite element models. The weld leg length and the flank angle on the main plate side are set at 11.0 mm and 142 degrees. The weld leg length on the gusset plate side is assumed to be 8.8 mm.

In order to reproduce the weld toe configuration in the as-welded joint and UIT operated joint, the AW-L model and the UIT-L model are constructed by measuring the weld toe part with a laser displacement sensor as shown in Figure 15. These are the series II models. The device for the measuring is KEYENCE/LK-080. The area of weld toe part measured is 6.0 mm × 4.0 mm. The measurement accuracy is 5 μm, laser spot diameter is 70 μm and the interval of measuring is 0.1 mm. The number of models of the AW-L and UIT-L is four, respectively.

As shown in Figure 15, round dents due to the impact of the pins are observed on the surface of the weld toe where UIT was given. In the series III models, the shape of the weld toe with UIT is modelled by circular dents. Here, five models considering the lap of the round dents were constructed as shown in Figure 16. In these models, lap length OL was paid to attention. The diameter of the circular dent is assumed to be 3.0 mm, and the lap length OL is assumed to be 1.0, 1.4, 2.0, 2.4 and 3.0 mm. The shape of cross section of the dent is assumed to be semielliptical and its depth is set at 0.8 mm. When lap

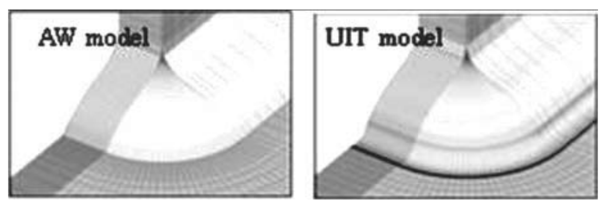

Figure 14 – Finite element model (constant toe shape)

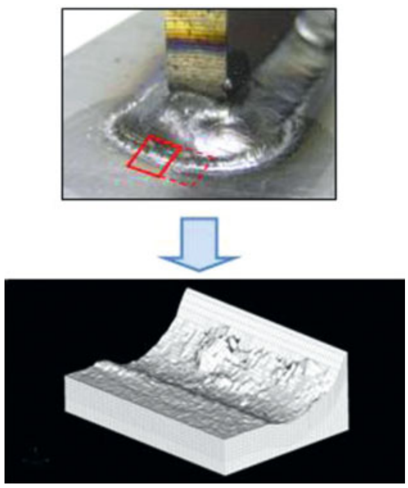

Figure 15 – Series II model

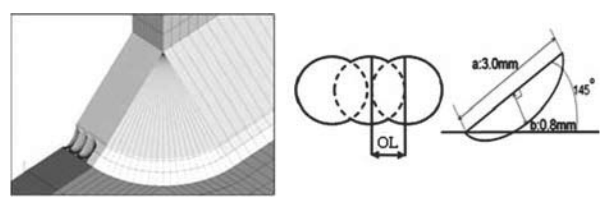

Figure 16 – Series III model

length OL is equal to 3.0 mm, the shape of the weld toe is smooth without the lap. These models are called UIT-R.

4.2 Results of Analyses

The stress concentration factors of the AW model, the UIT model, the AW-L model and the UIT-L model obtained from the analyses are shown in Table 4. The stress concentration factor of the AW model is 4.35, and that of UIT model is 2.81. The stress concentration factor ratio shown in the table is a value which is the ratio of the stress concentration factor of the AW model to that of the UIT model. If fatigue strength is assumed to be inversely proportional to the stress concentration factor, the fatigue strength of the UIT model increases to 1.55 times as that of the AW model. But the fatigue test results suggested that fatigue strength improvement ratio is only 1.03. The reason of this difference is considered that the weld toe shape of the UIT model shown in Figure 14 is different from the actual shape of the weld toe with UIT as shown in Figure 15. That is, the weld toe shape is not continuous but round dents are overlapped.

The stress concentration factor of AW-L models, which were constructed on the basis of measurement of weld toe shape with the laser displacement sensor, is 5.08-5.93, and the average is 5.57. This value is about 30 % higher than the AW model. This result means that a low value of stress concentration factor was obtained if the weld toe shape is modelled by ρ and θ and they are assumed to be continuously constant along the weld toe. But, the accuracy of reproducing the weld toe shape with the laser displacement sensor is uncertain because of the laser reflection property, the measurement accuracy, the spot diameter and so on. The stress concentration factor of four UIT-L models is from 4.21 to 5.21 and the average value is 4.66. Fatigue strength improvement ratio is 1.20 if stress concentration factor of UIT-L models is compared with that of AW-L models, and this value becomes close to 1.03 obtained by the fatigue test results.

Table 4 – Results of FE stress analyses

Model		Stress concentration	Stress concentration ratio
AW		4.35	–
UIT		2.81	1.55
AW-L	1	5.93	–
	2	5.68	–
	3	5.08	–
	4	5.60	–
	average	5.57	–
UIT-L	1	4.51	–
	2	4.81	–
	3	4.21	–
	4	5.12	–
	average	4.66	1.20

The analytical results of the UIT-R models are shown in Figure 17 and Figure 18 in which the location of maximum stress concentration and influence of the lap length on the stress concentration factor are examined. Figure 17 shows principal stress contour diagram in case of the lap length OL = 1.4mm. The location of the maximum stress concentration is not a deepest portion of the dent, and is the top part where the dents are overlapped. Figure 18 shows the relationship between the stress concentration factor and the lap length of dents OL. The stress concentration factor decreases as the OL value increases. This result may mean that it is preferable to operate UIT closely so that the dents come in succession as much as possible in order to ascertain the fatigue strength improvement from the standpoint of weld toe shape.

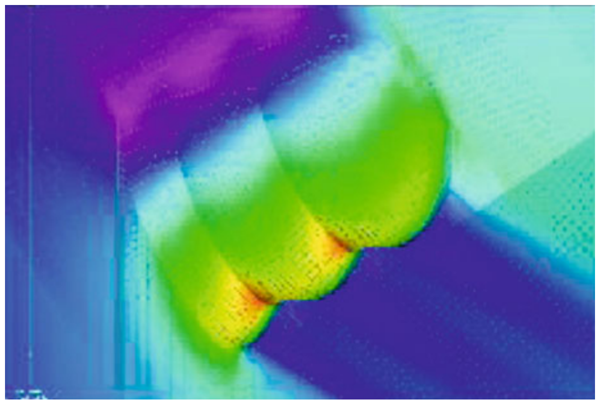

Figure 17 – Counter diagram of principle stress (OL=1.4 mm)

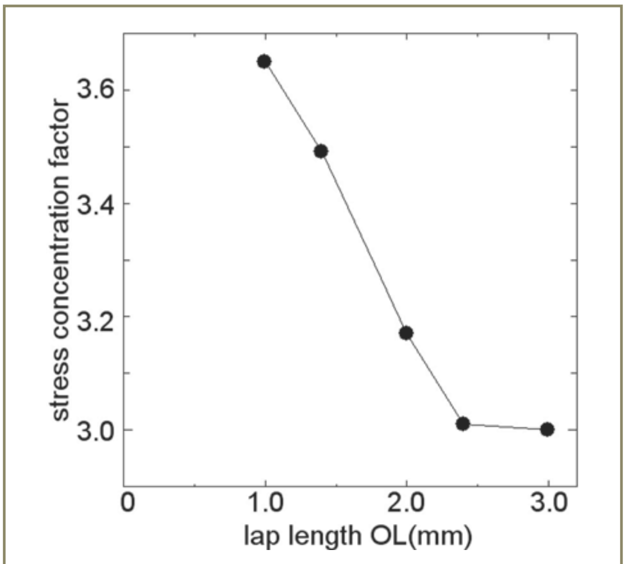

Figure 18 – Stress concentration factor and OL

5 Conclusion

The main results of the present study are as follow.

1. When UIT is given under no load, the effect of UIT on the fatigue strength improvement is remarkable in low stress ratio (R = 0). However, the effect becomes small in high stress ratio (R = 0.5) and large stress range. The reason of the fact is considered that the compressive residual stress introduced by UIT decreases or disappears at the weld toe due to local plastic deformation when UIT is given under no load and high stress. Therefore, the effect of UIT of the fatigue strength improvement is not obtained when the maximum stress is high. However, the effect of UIT on the fatigue strength is not dependent on only the upper limit stress but also the stress range.
2. A remarkable effect of the fatigue strength improvement is obtained when UIT is given under the load. When UIT is given under the maximum load, fatigue strength twice or more than that of as-welded joints can be expected even if stress ratio is high (R = 0.5).
3. The stress concentration reduction and the fatigue strength improvement are not remarkable from the standpoint of weld toe shape improvement by UIT. It is preferable to operate UIT carefully so that the dents come in succession as much as possible in order to reduce the stress concentration.

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