

# Clarification of mechanism of improvement effect of UIT on fatigue life of welded steel structure

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# 学 位 論 文 概 要

## Dissertation Summary

学位請求論文 (Dissertation)

題名 (Title) UIT処理による溶接部を有する鋼構造物の疲労寿命向上メカニズムの解明

Clarification of mechanism of improvement effect of UIT on fatigue life of welded steel structure

氏 名 (Name) 鈴木 環輝

学位論文概要 (Dissertation Summary)

**Abstract.** Ultrasonic impact treatment(UIT) is a remarkable post-weld treatment, which reduce not only in external stress concentration, but also in residual stress in a welded joints. Internal and surface stresses were investigated on UIT treated welded joints by neutron and X-ray diffraction method. We compared the cases where tensile stress stress was applied after UIT treatment was examined. The applied stresses at this time were 75% or 85% of the yield point, respectively. This paper discusses the effect of internal and surface residual stress and surface stress concentration after UIT on fatigue resistance by the comparison of fatigue experiments to predictions calculated with the results of the experimental investigations. As a result, the load after the UIT treatment caused plastic deformation in a part of the inside, which caused the redistribution of residual stress. It was also found that such changes in the internal residual stress state are the cause of the changes in the surface residual stress.

### Introduction

Steel structures are often subjected to cyclic loading, such as traffics. Sometimes these structures are damages by such cyclic loadings even if the stress induced by the loads are much smaller than yield stress. This type of the damage is called fatigue fracture. In general, fatigue strength falls greatly and in most cases the fatigue are found at a near-weld-toe-area, and it is well known that the fatigue life of welded joints is little influenced by the strength of steels but influenced by the residual stress and the high stress concentration near the weld toe. Thus, it is important to control the stress condition at this near-weld-toe-areas. To control the stress condition at the near-weld-toe-area, various methods such as grinding, tungsten inter gas(TIG) dressing, hammer peening, shot peening, laser peenig, low transformation temperature(LTT) welding consumable, have been developed and applied to weld toe. However, none of them can be said to be wholly satisfactory. Ultrasonic impact treatment (UIT) is a remarkable post-weld treatment, which convert ultrasonic wave to mechanical impact oscillations and peening the metal surface and give plastic deformation, and reduce in not only the external stress concentration through the formation of a smooth transition at the weld toe, but also in residual welding tensile stress and create favourable surface compressive stresses at the near-weld-toe-area and improve fatigue life. UIT is a registered trademark of Applied Ultrasonics, LCC.

UIT modify residual stress of not only the surface but also the internal, but it is not clear. So, the motivation of this study is to clarify the internal stress conditions after UIT, and understand

the effect of internal stress distribution on fatigue resistance, and final goal is to know how to control stress conditions by UIT to improve fatigue life of steel structure effectively. For this aim, it is important to know both the internal and surface stress conditions after UIT. Internal and surface stresses were investigated on UIT treated welded joints by neutron and X-ray diffraction method. This paper discusses the effect of internal and surface residual stress and surface stress concentration after UIT on fatigue resistance by the comparison of fatigue experiments to predictions calculated with the results of the experimental investigations.

## Experimental Procedures

### Specimens.

The non-load-carrying cruciform joints were welded using CO2 fillet welding with SM490 base metal plates according to JIS G 3106 and T49J0T1-1CA-UH5 flux-cored welding wire according to JIS Z 3313. UIT is applied to the weld toes of some specimens. The treatment was conducted using an Esonic<sup>TM</sup> 27 UIS made by Applied Ultrasonic and pins designed exclusively for UIT use (3mm tip radius and 3mm diameter) under the following conditions: frequency, 27kHz; power output, roughly 1kW; shifting speed, roughly 10mm/sec.

### Fatigue tests.

The fatigue tests were conducted for the specimens without and with UIT under the constant-amplitude loading in the stress range of 80~280 MPa and at a stress ratio of 0.1. For the experimental results, the number of loading cycles along the abscissa represents that cycle at which the specimen actually broke.

### Non-destructive surface shape evaluation by Laser.

The sectional shapes of a weld bead of the cruciform welded joints before and after UIT were measured by Laser Displacement sensor.

### Estimation of surface external stress concentration.

The stress concentration coefficient Kt for the cruciform welded joints before and after UIT are calculated using the estimation formula proposed by Tsuji with the weld toe radius  $\rho$  and other local dimension parameters of the joint [12].

### Non-destructive surface stress evaluation by X-ray diffraction method.

We performed non-destructive surface stress measurements by X-ray diffraction method. The surface stress at the weld-toe after UIT was determined by the  $\sin^2 \psi$  method using a conventional laboratory X-ray equipment. The Fe 211 diffraction by the characteristic X-ray of Cr-K  $\alpha$  radiation was used for stress measurements. For the comparison, we also measured a surface stress at the weld-toe before UIT.

### Non-destructive internal stress evaluation by neutron diffraction method.

We performed non-destructive surface stress measurements by the neutron diffraction method. Residual stress was evaluated in three directions, X, Y and Z. In the neutron diffraction method, a lattice constant under the stress-free condition is required when it comes to conducting triaxial stress analysis based on the measurement results for lattice plane spacings in three directions. For a specimen prepared under the same conditions as the specimen measured, the lattice constant that is obtained with a coupon sample prepared by electrical discharge machining at the same point as the measuring points was used as the lattice constant under stress-free conditions. Using the lattice constants decided by the above method as the lattice constants under stress-free conditions,  $a_0$ , we conducted a strain and stress analysis using Eq. 1 and Eq. 2 below. In Eq. 1 and Eq. 2,  $\varepsilon$ ,  $\sigma$ , E and  $\nu$  denote strain, stress, Young's modulus and Poisson's ratio, respectively. We used 211.41GPa as E and 0.2861 as  $\nu$ .

$$\varepsilon_i = (a_i - a_0) / a_0. \quad (i=X, Y, Z) \quad (1)$$

$$\sigma_i = E / (1 + \nu) \{ \varepsilon_i + \nu / (1 - 2\nu) (\varepsilon_X + \varepsilon_Y + \varepsilon_Z) \}. \quad (i=X, Y, Z) \quad (2)$$

## Experimental Results

### Fatigue tests.

Fig. 1 shows the experimental S-N curves (stress versus number of loading cycles to failure) obtained with the fatigue test results. In the high cycle fatigue conditions that the stress range are small, then the fatigue life of the specimens to which the UIT was applied were about forty times of that of those without the UIT(As-weld). On the other hands, in the low cycle fatigue conditions that the stress range is large, the fatigue life improvement effect of the UIT tended to be lower than that in the low cycle fatigue conditions.

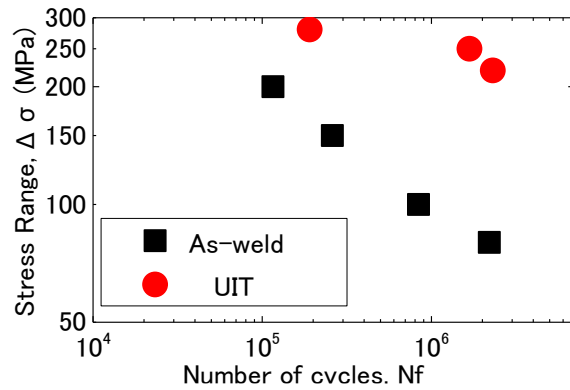


Fig. 1. Experimental S-N curves

### Surface shape evaluation by Laser.

The sectional shapes of a weld bead before and after UIT are shown in Fig. 5. Before UIT for an as-weld specimen, the sectional shapes of a weld bead toe radius  $\rho$  was roughly 0.25mm. After UIT, it increased to roughly 2.0mm through the formation of a smooth transition at the weld toe.

### Estimation of surface external stress concentration.

Using the measurement values of weld toe radius, the stress concentration coefficient  $K_t$  for the cruciform welded joints before and after UIT were calculated to 4.07 and 2.16, respectively.

### Non-destructive surface stress evaluation by X-ray diffraction method.

The surface stress at the weld-toe before UIT determined by the  $\sin^2 \psi$  method using a conventional laboratory X-ray equipment was 227MPa. This large residual tensile stress was supposed to be produced by the procedure that the weld metal has been locally heated and melted during welding, cooled and shrunk at the end of welding under constraint from the surrounding members. The surface stress at the weld-toe after UIT was -76MPa. This residual compressive stress was supposed to be introduced by a plastic flow which has been generated when the pin was pressed against the weld toe.

### Non-destructive internal stress evaluation by neutron diffraction method.

Fig. 2 shows the results of internal residual stress evaluation at weld-toe-area of a cruciform welded joint after UIT and after tensile load by neutron diffraction method. After tensile load, the absolute value tends to decrease at the peaks of the surface compressive residual stress and internal tensile residual stress. In addition, it can be seen that the amount of decrease is larger when the load stress is larger. The cause of such changes in the residual stress distribution is that plastic deformation occurs locally at the area of internal tensile residual and the surface stress changed to maintain the stress balance.

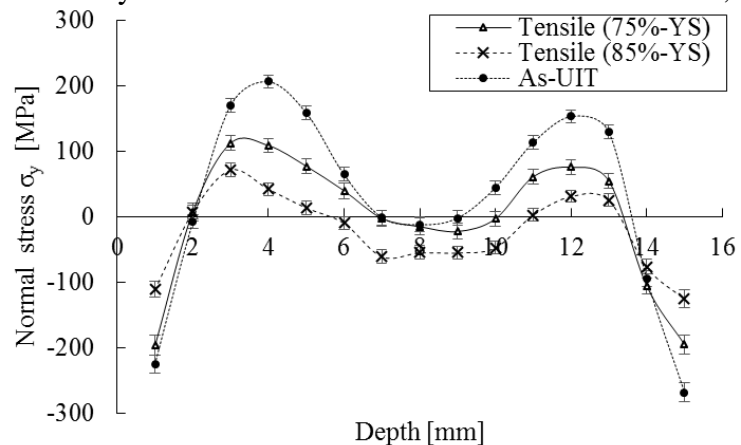


Fig. 2. Internal residual stress distribution before and after tensile load

## Discussions

### Estimation of fatigue life.

The Locally-Expanded Modified Goodman Diagram (LEMGD) that takes into account the steel strength, local stress concentration and local residual stress, and that permits estimating the fatigue life from calculated fatigue strength, is a simple technique to estimate fatigue life. Using LEMGD, we estimated the fatigue life for the specimens without and with UIT under the constant-amplitude loading in the stress range of 80~280 MPa and at a stress ratio of 0.1. In this technique, local surface stress  $\sigma_L$  at the weld toe is represented by Eq.3. In Eq.3,  $K_t$ ,  $\sigma_N$  and  $\sigma_{RS}$  denote stress concentration coefficient, nominal stress and residual stress, respectively. We used 4.07 as  $K_t$  and 227MPa as  $\sigma_{RS}$  for as-welded, 2.16 as  $K_t$  and -76MPa as  $\sigma_{RS}$  for UIT, respectively.

$$\sigma_L = K_t \times \sigma_N + \sigma_{RS}. \tag{3}$$

### Analysis of effects of UIT on fatigue strength.

Comparing of fatigue tests to estimations calculated with surface stress concentration and surface residual stress and without internal residual stress, internal stress can be affect o fatigue life. In high cycle fatigue conditions that the stress range are small, then experiments and estimations are almost same. In this case, internal stress doesn't affect to the fatigue life, and the fatigue life is strongly affected by surface stress conditions, that are surface stress concentration and surface residual stress. In this case, to improve fatigue life of steel structure by UIT, we should control just surface stress conditions, that are surface stress concentration and surface residual stress. On the other hands, in the low cycle fatigue conditions that the stress range is large, the experiment is much smaller than the estimations.

To understand the reason why the experiment are much smaller the estimation in this case, we corrected the estimation of a fatigue life of this case with the surface residual stress measured by X-ray method after the first cycle in fatigue tests and compare the corrected estimation to actual fatigue test. Then the corrected estimation and the actual fatigue test are almost same. The reason why the experiments are much smaller than the predictions in this case was turned out to be that the redistribution occurred because of internal high tensile stress in the first cycle in fatigue tests and the surface residual compressive stress after UIT has changed to tensile stress. In this case, the fatigue life can be affected by the internal stress conditions at near-weld-toe-area, and we should control both surface and internal conditions.

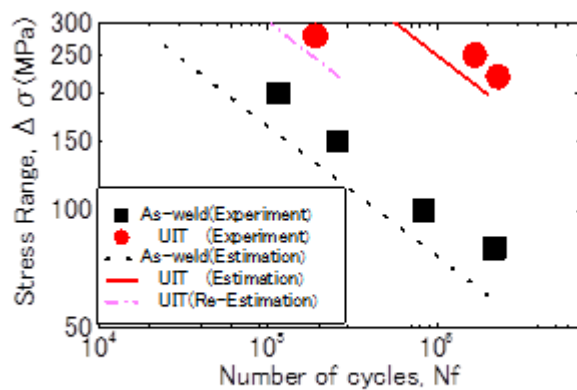


Fig. 3. Experimental and estimated S-N curves.

### Summary

Internal stress distribution was clarified on UIT treated cruciform welded joints by neutron diffraction method. Comparing the fatigue experiments to predictions calculated with the results of the experimental investigations, the effect of UIT on fatigue life is turned out that in mild fatigue tests conditions, the fatigue life is strongly affected by the surface stress conditions. In this case, to improve fatigue life of steel structure, we should control just surface stress conditions by UIT. On the other hands, in severe fatigue tests conditions, the fatigue life is not only affected by the surface stress conditions, but also can be affected by the internal stress conditions. In this case, we should control both surface and internal stress conditions by UIT.

## 学位論文審査報告書（乙）

1. 学位論文題目（外国語の場合は和訳を付けること。）

UIT 処理による溶接部を有する鋼構造物の疲労寿命向上メカニズムの解明

2. 論文提出者 氏名 ふりがな すずき たまき  
鈴木 環輝

3. 審査結果の要旨（600～650 字）

当該学位論文に関し、令和 3 年 2 月 1 日に第 1 回学位論文審査委員会を開催し、提出された学位論文および関連資料について詳細に検討した。同日に口頭発表の後、第 2 回学位論文審査会を開催し、慎重に協議の結果、以下の通り判定した。

申請者は、本学位論文において、疲労強度の保障において残留応力の管理が重要とされている十字溶接継手を有する鋼材を対象とし、パルス中性子応力測定法を適用して溶接止端部直下の内部の残留応力状態の解明に取り組んでいる。また、新しい残留応力の付与技術である超音波衝撃法（UIT）を導入し、溶接後に UIT を適用した直後と共に、過大荷重が付与された場合の内部残留応力状態について、それぞれ明らかにした。次に、疲労強度との関係について検討を行い、疲労の 1 サイクル目の直後に材料の内部または表面における局所的な塑性変形の発生により、残留応力の再分布が起こる結果、疲労寿命が大きく影響されることを明らかにした。さらに、以上の知見を基礎として、正確に疲労寿命を予測する方法を考案し、その有効性を明らかにした。

以上のように、本研究は十字溶接した鋼材の疲労強度に対する残留応力の影響の解明に貢献するものであり、工業的価値が高く、博士（工学）の学位に値すると判定した。

4. 審査結果 (1) 判定（いずれかに○印） 合格 ・ 不合格

(2) 授与学位 博士（工学）