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Application of UIT to Suppress Fatigue Cracks of Welded Structures

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Abstract

Use of ultrasonic impact treatment (UIT) is expanding for suppressing fatigue cracks of welded steel structures. It is a method for improving the shape of weld toes, where cracks are likely to occur, and introducing compressive residual stress there. Although it is very effective at extending the fatigue life of welded joints, its effect is sometimes reduced depending on the load conditions of the structure. For wider and effective application of UIT, this paper describes the factors that have to be considered in its practice.

1. Introduction

Ultrasonic impact treatment (UIT)^{*1, 1, 2)} is a kind of peening treatment, whereby ultrasonic impact is applied to welded joints using metal pins connected to a vibration source. The impact causes the material in the surface layer to flow plastically and introduces compressive residual stress near the surface. Application of UIT is gradually expanding to wide varieties of welded structures, either existing or new, in appreciation of the ease of practice and the dramatic effect to improve the fatigue strength of welded joints. It is effectively used in Japan, especially for the manufacture and construction of bridges, ships, and construction machinery, and also as a common measure against the fatigue of welded joints and weldingrepaired parts. Among roughly 4800 technologies registered in the New Technology Information System (NETIS) of the Ministry of Land, Infrastructure, Transport and Tourism, UIT was selected as one of the 21 recommended technologies in 2014,3 which is expected to boost wider application of the method.

In general, the fatigue strength of welded joints does not vary depending on the strength of the steel, but recent studies revealed that the effect of UIT against fatigue of welded joints differ depending on factors such as the steel material, the conditions of use of the structure, and the treatment quality of UIT.^{4, 5)} In addition, regarding the conditions of use, the effect of UIT changes depending on the excessive loads and the stress ratio on the structure. There may be cases where no improvement is obtained, and the effect is different depending on the quality of the treatment, its sequential order, etc. Considering the above, this paper explains the effect of UIT on the fatigue characteristics of welded joints and effective methods of its application.

*1 UIT technology (ESONIX[™]) is a peening technology held by UIT., L.L.C. in the United States. While there have been various studies to quantitatively estimate the effect of UIT, the results of such studies are not reflected in relevant standards, but the direction of the UIT effect estimation is gradually becoming clear. In view of this, the present paper also outlines the methods of quantitative estimation of the UIT effect and the latest trend of the estimation method in relevant standards.

2. Fatigue of Welded Structures

As is well known, the higher the tensile strength of steel, the higher its fatigue strength becomes.^{6,7)} The fatigue properties of a welded joint, on the other hand, do not change depending on the steel strength. Hence, since the design fatigue strength of welded joints cannot be increased, it is sometimes hard to make structures lighter by using high-strength steels when high fatigue strength is required.

Fatigue cracks occur as a result of local and microscopic plasticizing of steel due to repeated loads, which means that higher steel strength brings about higher fatigue strength. At welded joints, however, stress concentrates at weld toes and fatigue cracks occur more easily there than in smooth base metal portions. What is more, at welded joints there is residual tensile stress, which increases in proportion to the steel strength and cancels the increase in the fatigue strength. This is the reason why improving the fatigue strength of welded joints using high-strength steels is difficult.

There are two measures widely practiced to improve the fatigue strength of welded joints:⁸⁾ one is to decrease stress concentration at portions where fatigue cracks are likely to occur and the other is to control the residual tensile stress at weld toes, either mitigate it or change it into compressive side.

Typical practice of the former includes grinding of weld toes and smoothing them by melting by tungsten inert gas (TIG) welding, and that of the latter includes annealing, various types of peening, and

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use of low transformation temperature (often called LTT) welding consumable. UIT is a kind of peening treatment to introduce compressive residual stress to weld toes. But UIT is not only to improve residual stress condition but also to improve the shape of weld toe.

3. More Details of UIT^{1, 2, 9–12)}

3.1 Device and practice

As stated above, UIT is a kind of peening treatment method applying an ultrasonic impact phenomenon, and it introduces compressive residual stress to the subsurface layer near the point of impact.

As given in **Fig. 1**, a UIT device comprises an ultrasonic wave generator, a hand tool, and a cooler; the generator sends electric signals to the hand tool, which changes them into ultrasonic vibration in the axial direction using a transducer of a magnetostrictive material. The ultrasonic vibration is amplified by a waveguide, several tens of micrometers in amplitude, and the pins at the tip of the hand tool hit the object steel. The pins are softly fixed to a holder such that they transmit the vibration to the object material without loosening or dislocating. Since the magnetostrictive material generates heat, the inside of the hand tool is water cooled.

In the peening process by UIT, the pins contacting the object steel are excitated by the ultrasonic vibration, hits the material repetitively to cause its surface layer to flow plastically, the surface to deform according to the shape of the pinheads, and compressive residual stress to form in the subsurface layer near the point of impact.

Since a weld toe, where fatigue cracks are likely to occur, is in an angle between the base metal and the weld bead, as seen in **Fig. 2**, it is easy to strike a welded joint selectively and efficiently at the toe of the bead by sliding the impact pins along it. Impact pins used for



Fig. 2 Weld toe processing by UIT

treating welded joints usually have a diameter of 3 mm. According to common practice, the stress concentration due to the weld toe shape is mitigated by applying the impact until the shape of the pinheads is printed thoroughly to form a shallow and continuous groove masking the entire weld toe line. When the pinhead shape is completely printed, due to the decrease of the mean reaction stress to the contact part, further deformation becomes difficult and the groove depth is usually automatically limited to 0.2–0.3 mm.

Figure 3 compares the fatigue lives of cross weld joints of EH36 class steel (under Class NK standard) with and without UIT at weld toes (pin diameter 3 mm, frequency 27 kHz, power 1 000 W).^{2, 3)} The graph shows that the fatigue lives of the specimens with UIT are about 10 times those of the specimens without treatment, evidencing significant improvement effect of UIT.

3.2 Mechanism of fatigue crack prevention at welded joints

The mechanism of UIT to prevent fatigue cracks from occurring at weld toes is presumed to show, as illustrated in **Fig. 4**,²⁾ through the combination of (a) compressive residual stress at weld toes resulting from the impact, (b) decrease in the stress concentration at weld toes thanks to the shape modification, and (c) formation of a hardened structure of fine crystal grains, called a white layer, in the surface layer; of these, the compressive residual stress is considered most significant.

As stated earlier, fatigue cracks are considered to result from the repetition of local and microscopic plastic deformation of steel due to repeated loads. When UIT is applied, as **Fig. 5** illustrates, the stress concentration at weld toes is reduced, the stress amplitude there becomes relatively small, and the compressive residual stress simultaneously decreases the local mean stress, which makes plastic



Fig. 3 UIT effect seen in fatigue test of cruciform welded joints



Fig. 4 Fatigue strength improvement factor in UIT technique



Fig. 5 Fatigue strength improvement effect of UIT

deformation of the steel unlikely and hinders the formation of fatigue cracks. Since the fatigue strength of steel increases with its tensile strength, the fatigue strength of the surface layer, where cracks initiate, is high as its structure is hardened. The fatigue crack preventive effect of UIT is considered to result from the combination of these factors.

4. Fatigue Properties of Welded Joints after UIT

In general, the fatigue strength of a welded joint does not depend on the strength of the base metal. The fatigue design guidelines issued by the International Institute of Welding (IIW), the Japanese Society of Steel Construction (JSSC), etc. define S-N curves for different types of welded joints. While Nippon Steel & Sumitomo Metal has demonstrated that UIT remarkably improves the fatigue strength of welded joints, regardless of the joint type,^{2, 13–21}) we have also indicated that UIT may not bring any positive effect under some conditions, clarified the conditions where UIT is effective, and called for attention in its practice. The factors that influence the effect of UIT to improve fatigue strength and the conditions are presented below.

4.1 Effects of pre-loading

Since the fatigue crack preventing effect of UIT is obtained owing to the compressive residual stress introduced to weld toes, it may be decreased when the compressive stress is reduced. In relation to this, the influence of preloading on the fatigue properties improvement effect was examined as follows.

4.1.1 Specimens and test conditions

Test pieces of a non-load-carrying cruciform joint, as shown in **Fig. 6**, were prepared by welding 20-mm-thick plates of SM490B under JIS G 3106, and subjected to the prescribed preloading and to the fatigue test at maximum loads lower than the preload. Note that, to prevent fatigue fracture by the chucks of the testing machine, the center portion of the test pieces to which UIT was applied was made narrower, as shown in Fig 6,¹³ but those without UIT had a straight shape.

To see the change in the compressive residual stress at the weld toe introduced by UIT, it was measured before and after applying the preload; **Fig. 7** shows the groove formed by UIT and the line along which the residual stress was measured.

4.1.2 Test results

The change in the residual stress near the weld toe before and



Fig. 6 Cruciform joint test specimen for UIT

after preloading is given in **Fig. 8**.¹³) It is clear from the graph that, with either a tensile loading by 90% of the yield stress (0.9YS) or a compressive loading by 60% of the yield stress (0.6YS), the compressive residual stress is lower than that immediately after UIT, but preloading of this magnitude does cancel the residual stress.

Figure 9¹³⁾ shows the results of the fatigue test of the welded joint specimens. The test demonstrated that, with specimens after



Fig. 7 UIT cruciform joint and residual stress measurement point



Fig. 8 Change in residual stress near weld toes due to preloading



Fig. 9 Influence of preloading on fatigue strength improvement effect of UIT

UIT, the fatigue strength after compressive or tensile preload was slightly lower than that without preload, but in either case, it was far higher than that of the specimens without UIT (as-welded without preload). The graph includes the test results of comparative specimens treated by grinding; here, it is clear that the specimens after UIT, even with the tensile (0.9YS) or compressive (0.6YS) preload, maintain the same level of fatigue strength as that of grinder-treated ones, or better.

Note here that a compressive preload implies an extra compressive load in addition to the compressive stress by UIT, and when a greater compressive load is applied to the joint, it is feared to yield and release the compressive residual stress. However, the following is presumed: stress concentration is reduced by the shape modification by UIT; tensile residual stress is introduced by UIT to the internal region beneath the surface layer, where UIT introduced the compressive residual stress; and all these serve to resist yielding under the extra compressive load and thus prevent plastic deformation (yielding). Since it is difficult to apply large axial compressive loads by the fatigue test equipment, to confirm the effects of greater compressive loads, using other types of loading such as bending with a larger test facility, which is yet to be tried, is necessary.

4.2 Influences of steel strength ^{3, 5, 13–18)}

The magnitude of the compressive residual stress introduced to weld toes by UIT depends on the strength of the steel: the higher the steel strength, the greater the compressive residual stress. Hence, better fatigue strength improvement effect of UIT can be expected with high strength steels.

4.2.1 Influences of steel strength and maximum load on fatigue strength of welded joint

Out-of-plane gusset joints, as shown in **Fig. 10**, were prepared using three steels of different tensile strengths, SBHS400, 500, and



Fig. 10 Out-of-plane gusset joint fatigue specimen

700 under JIS G 3140, and subjected to fatigue test. The S-N curves obtained through the test and rearranged in terms of maximum stress are given in Fig. 11. The larger the maximum stress, the smaller the fatigue life improvement effect of UIT becomes with any of the steels. This seems to relate to the decrease in the fatigue life improvement effect of UIT with increasing preload seen with Fig. 9, as discussed in Subsection 4.1. With high-strength steel such as SBHS700, however, the effect of UIT is little affected even under high maximum stress; for example, at a maximum stress of 268 MPa or above, where UIT does not show any tangible effect with SBHS400, the fatigue strength of SBHS700 definitely increases and so does its fatigue life. It is widely known that the fatigue strength of welded joints without any post-treatment is not improved even with a base metal of high strength. In contrast, the effect of UIT to improve the fatigue strength of welded joints is larger with base metal of higher strength. This is a notable characteristic effectively applicable to structural parts where high-strength steels are unsuitable from the perspective of fatigue design. How to predict the influences of steel strength will be discussed in more detail later in Section 5.

4.2.2 Influence of stress ratio 4, 5, 13-18)

The test result given in Fig. 11 in the previous subsection is rearranged in terms of stress ratio and shown in Fig. 12. On steel road bridges and similar structures, the load of traffic is imposed in addition to the dead weight of the bridge. In such a case, stress ratio sometimes increases significantly at welded joints, where the occurrence of fatigue cracks should be considered in the design stage. As is clear from Fig 12, the fatigue strength improvement effect of UIT is reduced under high stress ratio, and furthermore, when both stress ratio and maximum load are high, there are sometimes cases where UIT does not show any improvement effect. This is because, while with as-welded joints without UIT the stress ratio at weld toes, where there is tensile residual stress, remains locally high even under changing ratio of nominal stress on the members, with welded joints to which UIT is applied (hereinafter called UIT joints), weld toes are locally under compressive force owing to the compressive residual stress. Therefore, when repetitive loads are applied from outside, the local stress ratio changes markedly from negative to positive, which leads to a substantial change in effective stress affecting the fatigue of the joint, and consequently, its fatigue strength



Fig. 11 Influence of the steel strength on the effect of UIT



Fig. 12 Influence of the stress ratio on the effect of UIT



Fig. 13 Effect of stress ratio on fastigue characteristics of UIT joints

changes significantly. The behavior of the local stress at weld toes is schematically illustrated in Fig. 13. The influences of stress ratio on cruciform joints have been studied, and the fatigue strength improvement effect of UIT has been confirmed through reversed loading tests.¹³⁾ Prediction of the effects of stress ratio will be discussed in Section 5.

4.2.3 Influence of work quality and error

Regarding the work quality of UIT, it is recommended that original weld toes be covered completely by the groove formed by the pinheads, because if some parts of original weld toes are left as they were, stress will concentrate there and the improvement effect may be lost. In addition, if the shape of weld toes is not good or the flank angle is too large for reasons of welding materials or work conditions, thorough treatment of the toes may take time. Such treatment may sometimes leave crack-like defects, and if they are too deep, they may spoil the improvement effect of UIT. Sometimes stress ratio increases substantially at weld toes owing to the angular deformation resulting from welding. Since the fatigue strength of UIT joints changes significantly depending on stress ratio as explained, more care must be taken than that for joints without UIT, which are comparatively less affected by the stress ratio.

5. Estimation of UIT Effect ^{17, 18)}

As described above, factors having negligibly small effects on as-welded joints may have significant influence on the fatigue characteristics of UIT joints, and it is necessary to estimate the fatigue characteristics in consideration of such factors. There are two methods for estimating the fatigue characteristics of UIT joints: one is that by which the calculation of fatigue life of a member on the basis of the fatigue crack growth analysis in consideration of the loading history that affects crack propagation, and the residual stress and stress concentration at weld toes to which UIT is applied; and the other is that estimation of S-N curve without using a crack propagation rate, under the consideration of complicated loading history. 5.1 Analysis of fatigue crack propagation ¹⁹⁻²²

Nippon Steel & Sumitomo Metal has worked out a practically accurate system for estimating fatigue lives of welded structures¹⁹⁾ considering the stress concentration and residual stress in their members and random loads. An example flow diagram for the estimation of fatigue life of a welded joint up to crack penetration is given in Fig. 14.

The system estimates fatigue life of a welded structure, combining the analysis of their stress intensity factors using the weighted function method and simulation of crack opening/closing 20, 21) applying the strip yield model, and sequentially analyzing the behavior of crack propagation from assumed very small initial surface cracks at weld toes. By this, it is possible to (a) calculate the stress intensity factors considering the effects of the stress concentration due to the joint shape and the complicated residual stress distribution due to welding work and UIT, (b) estimate crack opening/closing load from the analysis of plastic deformation behavior of crack tips and the contact of crack faces, and based on these, (c) accurately esti-

mate the fatigue life of a welded structure in consideration of the influences of load sequence and stress ratio.

When applied to a UIT joint, the system supposes that small initial cracks are present in the UIT groove, calculates the stress intensity factor in consideration of the stress concentration due to the groove and the shape of growing cracks, and based on these, estimates crack propagation. An example of fatigue life estimation from crack propagation calculation by the above method is given in Fig. 15. Note here that the fatigue crack propagation rate proposed in the fatigue design guidelines of JSSC is applied to the case with the constant load amplitude condition.

Note also that, when loads are repeated in varying conditions, crack growth is slowed down by their opening/closing under lower loads following a large load, and it is presumably better for higher accuracy to use for the fatigue crack propagation calculation of a crack opening/closing model such as the one used for FLARP²³⁾ and the like.

To precisely estimate the service life of welded structures under residual stress, accurate data on the distribution of residual stress is



Fig. 14 Prediction flow of fatigue life of welded joints



Fig. 15 Fatigue life prediction of UIT joints based on crack propagation analysis

indispensable. Nippon Steel & Sumitomo Metal employs the nondestructive neutron diffraction technique to measure three-dimensional distribution of residual stress in combination with elasto-plastic thermal stress analysis to enable the evaluation of complicated distribution of residual stress in welded joint members.^{24, 25)}

5.2 Prediction of S-N curves

The IIW, specifically its XIII Committee, defined various types of peening treatment using ultrasonic impact (such as UIT) or pneumatic impact devises as the high-frequency mechanical impact (HFMI) treatment, and Dr. Marquis and his team began studies to clarify recommendable S-N curves for different kinds of HFMI treatment.²⁶⁾ The basic philosophy of the S-N curves is linked with IIW's fatigue classification of welded joints, commonly referred to as FAT; different curves have been proposed considering the influences of steel strength and stress ratio as explained in Section 4. Figure 16 shows examples of S-N curves for HMFI-treated joints.

While in recommended measures against fatigue of welded joints,8) the IIW had proposed S-N curves applicable to hammer or needle peening, which has an effect similar to that of HFMI treatment, the newly proposed curves are based on a totally different approach: steels up to the strength of 950 N/mm² are classified into four grades; the FAT class of a welded joint is raised by one grade when the strength class of the base metal is higher by one grade; the improvement effect of HFMI treatment decreases with increasing stress ratio R when R > 0; and no improvement effect is obtained when $R \ge 0.52$

Note, however, that the philosophy of these S-N curves does not include the cases where residual stress changes owing to factors such as excessive loads and heat treatment, and therefore, the curves may not represent the real joint fatigue strength accurately.

As stated earlier in 2.4.3, the fatigue strength of welded joints changes significantly depending on the work quality of UIT, and this is true also with other methods of HFMI treatment. The XIII Committee of the IIW discussed the matter and issued quality control recommendations.²⁷⁾

Since there is strong tensile residual stress at as-welded toes, local stress ratio is naturally high, yielding occurs comparatively easily there, local tensile stress has reached its peak, and the change of stress ratio due to angular deformation is small. With UIT, on the other hand, stress ratio at weld toes changes drastically from negative to positive, and the change in fatigue strength due to angular deformation is presumed to be relatively large. Figure 17 compares



Fig. 16 S-N curve prediction for HFMI joint



Fig. 17 Effect of angular deformation on fatigue life of UIT joints

the fatigue strength of the out-of-plane gusset joints, including the decrease due to the angular deformation of the test piece and that after readjustment of the decrease. Here, because of angular deformation, some specimens were loaded under conditions where the test load range was higher than that without the deformation by 80 MPa or more, or the stress ratio was higher by 0.1 or more, which may have resulted in a rating completely different from the real one; in fact, the ratings of some specimens were different by two grades or more according to the classification in the fatigue design of steel structures of the JSSC. As has been stated, the apparent fatigue strength of UIT joints change significantly depending on the use condition, and there are cases where expected fatigue strength improvement is not obtained. In applying UIT, therefore, it is necessary to decide the applied loading conditions of the structure and to estimate the improvement.

Nippon Steel & Sumitomo Metal has proposed its own approach to the prediction of S-N curves for UIT joints,^{17, 18}) paying attention to the fact that the change in residual stress in a UIT joint dependent on the conditions of repetitive loads has significant influence on its service life, and aimed at establishing a method of estimating the service life of welded joints. By this approach, with attention being paid to the residual stress in weld toes, the steel strength and local stress concentration, S-N curves are predicted on the basis of (a) the estimation of the maximum stress at which a decease occurs to the compressive residual stress that was introduced by UIT in consideration of high stress (or fatigue limit) up to which the compressive residual stress apparently prevents fatigue cracks, and (c) the S-N curves of as-welded joints. Further studies are being conducted to raise the method's prediction accuracy.

The above approach combines a method for estimating fatigue strength using the locally-expanded modified Goodman diagram (LEMGD) considering local residual stress, and another for estimating the condition where the distribution of the compressive residual stress introduced by UIT is reduced by excessive and cyclic loads, cancelling the improvement effect. **Figure 18** shows the basic concept of the estimation of the S-N curve for a UIT joint.

Figure 19 shows the change in the residual stress near weld toes of a UIT joint under different cyclic loading conditions; here, the specimens are out-of-plane gusset joints of SBHS700. The graph in-



Fig. 18 Proposed prediction method of S-N curve for UIT joint



Maximum nominal stress (σ_{Nmax}) , MPa

Fig. 19 Effect of the maximum nominal stress on residual stress change at the weld toe due to cyclic loading

dicates that cyclic loading at high stress ratios significantly decreases the introduced residual stress and damages the fatigue life improvement effect of UIT. On the other hand, at low stress ratios, the decrease in the residual stress is small, and the fatigue life improvement effect is presumed to last longer, even if the stress amplitude is large. At present, no methods are available for accurately predicting the change in the residual stress. However, to effectively apply the service life improvement effect of UIT for newly welded joints as well as those repaired by welding after long use, establishing methods for adequately predicting the change in the residual stress is necessary. Such methods will also be useful for clarifying the conditions where UIT is effective.

6. Closing

UIT is very effective at enhancing the fatigue strength and extending the fatigue life of welded joints. Different from conventional methods of shape improvement by grinding and the like, UIT takes advantage of improvement of residual stress, and hence, the conditions where it is effective are different from those of conventional methods. The reliability of welded structures can be enhanced with respect to fatigue, and they can be made lighter using high-strength steels when the fatigue life improvement effect of UIT is appropriately applied in consideration of the characteristics.

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