Effect of Ultrasonic Impact Treatment on Residual Stress and Fatigue Properties of Q345 Welded Joints

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Abstract. For the welding joints of Q345 materials commonly used in construction machinery, ultrasonic peening equipment is used to treat the heat affected zone and weld toe under different parameters, and the residual stress value before and after impact is tested by blind hole method, and the number of cycles under different stress ranges is tested by using a fatigue tester. The results show that the ultrasonic impact treatment can effectively eliminate the welding residual stress, and the reduction rate reaches 80\%-130\%; Increasing the ultrasonic impact current value can improve the impact force, causing greater plastic deformation and microscopic dislocation structure changes on the surface of the heat affected zone, thereby increasing the residual stress reduction rate; Increasing the impact time value has no significant effect on the residual stress reduction rate; the un-fusion caused by the bottom welding in the one side welding both sides formation is the root cause of the premature fatigue failure of the sample; Increasing the ultrasonic impact current value can increase the residual stress reduction rate, and form a smooth transition at the weld toe, reducing stress concentration, and thus improving the fatigue performance of the joint.

1. Introduction
The fusion welding method is the main processing and manufacturing method of engineering mechanical structural parts, and the welded joint is generally composed of a weld seam, a fusion zone, a heat affected zone and a base metal. The heat-affected zone is formed by the uneven heating of the welding heat input to the base metal, which is often the fragile position of the welded joint, which is reflected in two aspects: one is the change of the structure, the grain grows, the embrittlement, etc.; on the other hand, there is welding residual stress. At the junction of the weld metal and the heat-affected zone, that is, at the weld toe, there are geometric discontinuities such as weld reinforcements and undercut, resulting in a decrease in joint performance, especially fatigue resistance sensitive to stress concentration.

Ultrasonic peening uses high-power energy to push the impact head to impact the surface of the metal object at a frequency of about 20,000 times per second. High-frequency, high-efficiency and large energy under focusing cause large compression plastic deformation of the metal surface, which can
effectively improve the surface topography of the weld toe, reducing the stress concentration factor; at the same time, it can effectively change the original stress field and produce beneficial compressive stress [1]. Ultrasonic peening of welded joints can effectively improve the performance of engineering machinery structures and improve the safety and reliability of the whole machine.

2. Test methods and processes
In this paper, HY2050G ultrasonic peening equipment is used to ultrasonically impact the welded joints of Q345 materials commonly used in construction machinery. The residual stress in the heat affected zone of welded joints is measured by blind whole method. The frequency of welding joints is measured by high frequency fatigue testing machine. Furthermore, the effects of different ultrasonic impact treatment processes on the residual stress and fatigue properties of welded joints were studied.

During the test, the welding test plates are butt welded plates, a total of 16 pieces. The welding method was gas shielded weld, the welding wire was ER50-6 solid cored welding wire, and one side welding both sides formation. The plates 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 are used for testing the residual stress of the weld, and the heat affected zone is treated by ultrasonic peening, as shown in figure 1; Test plates A, B, C, D, E, and F were used for fatigue testing, and ultrasonic peening was used to treat the weld toe. The ultrasonic peening frequency is 20 kHz, and the impact current value and the impact time value are shown in table 1.

![Figure 1. Sketch map of UIT for welding sample board.](image)

**Table 1. Technological parameters of UIT.**

| Test Number | No-load Current I (A) | Impact Time T (s) | Remark                                      |
|-------------|-----------------------|-------------------|---------------------------------------------|
| 1           | 2.2(I1)               | 100(T1)           | UTI for topside weld                        |
| 2           | 2.7(I2)               | 100(T1)           | UTI for topside weld                        |
| 3           | 3.3(I3)               | 100(T1)           | UTI for topside weld                        |
| 4           | 2.2(I1)               | 250(T2)           | UTI for topside weld                        |
| 5           | 2.7(I2)               | 250(T2)           | UTI for topside weld                        |
| 6           | 3.3(I3)               | 250(T2)           | UTI for topside weld                        |
| 7           | 2.2(I1)               | 400(T3)           | UTI for topside weld                        |
| 8           | 2.7(I2)               | 400(T3)           | UTI for topside weld                        |
| 9           | 3.3(I3)               | 400(T3)           | UTI for topside weld                        |
| 10          | 0(I0)                 | 0(T0)             | Untreated                                   |
| A           | 0(I0)                 | 0(T0)             | Untreated                                   |
| B           | 1.7(I4)               | 250(T2)           | UIT for both sides weld                     |
| C           | 2.5(I5)               | 250(T2)           | UIT for both sides weld                     |
| D           | 0(I0)                 | 0(T0)             | Untreated                                   |
| E           | 1.7(I4)               | 250(T2)           | UIT for topside weld and milling for backside weld |
| F           | 2.5(I5)               | 250(T2)           | UIT for topside weld and milling for backside weld |
After the ultrasonic impact treatment, the residual stress of the symmetric position of the heat-affected zone on both sides of the weld was tested by the stress tester of model HK21A, and the test point was 2 mm away from the weld toe [2]. The test plates under each ultrasonic impact treatment parameter test three stress points 1*, 2*, 3*, and the distance between adjacent test points is greater than 20 mm, correspondingly, the other side does not impact the heat affected zone at the symmetrical position test three Points 1, 2, 3, as shown in figure 1.

The test plates of A, B, C, D, E, and F were processed into fatigue samples, and the fatigue test of the butt plates was carried out using a high-frequency fatigue tester model GPS200. The stress ratio R was 0.1, the stress range and the stress extremes as shown in table 2.

### Table 2. Parameters of fatigue tests.

| Group Numbers | Sample Number | Stress Range $\Delta \sigma$ (MPa) | Maximum/Minimum Stress $\sigma_{\text{max}}/\sigma_{\text{min}}$ (MPa) |
|---------------|----------------|-----------------------------------|-------------------------------------------------|
| A (Non-UIT)   | A1 171         | 190/19                            |                                                |
|               | A2 180         | 200/20                            |                                                |
|               | A3 198         | 220/22                            |                                                |
|               | A4 207         | 230/23                            |                                                |
|               | A5 216         | 240/24                            |                                                |
| B (1.7A Impact Current) | B1 216 | 240/24                            |                                                |
|               | B2 225         | 250/25                            |                                                |
|               | B3 243         | 270/27                            |                                                |
|               | B4 252         | 280/28                            |                                                |
|               | B5 288         | 320/32                            |                                                |
| C (2.5A Impact Current) | C1 180 | 200/20                            |                                                |
|               | C2 198         | 220/22                            |                                                |
|               | C3 216         | 240/24                            |                                                |
|               | C4 243         | 270/27                            |                                                |
|               | C5 270         | 300/30                            |                                                |
| D (Non-UIT)   | D1 252         | 280/28                            |                                                |
|               | D2 260         | 288.89/28.89                      |                                                |
|               | D3 270         | 300/30                            |                                                |
|               | D4 288         | 320/32                            |                                                |
|               | D5 333         | 370/37                            |                                                |
| E (1.7A Impact Current) | E1 243 | 270/27                            |                                                |
|               | E2 260         | 288.89/28.89                      |                                                |
|               | E3 270         | 300/30                            |                                                |
|               | E4 288         | 320/32                            |                                                |
|               | E5 333         | 370/37                            |                                                |
| F (2.5A Impact Current) | F1 225 | 250/25                            |                                                |
|               | F2 260         | 288.89/28.89                      |                                                |
|               | F3 270         | 300/30                            |                                                |
|               | F4 288         | 320/32                            |                                                |
|               | F5 333         | 370/37                            |                                                |

3. Test Results and Analysis

3.1. Stress Test Results and Analysis of Test Plates without Ultrasonic Impact Treatment

The maximum principal stress values of the heat affected zone on both sides of the weld of No. 10 test plate without ultrasonic impact treatment are shown in Table 3 below. The positive stress value represents tensile stress and the negative stress value represents compressive stress.

### Table 3. Results of residual stress with non-UIT.

| Test Point | 1 | 1* | 2 | 2* | 3 | 3* |
|------------|---|----|---|----|---|----|
| Maximum Principal Stress (MPa) | 317.61 | 305.75 | 305.91 | 328.99 | 310.95 | 313.96 |
| Difference | 3.9% | 7.5% | 1% |

From table 3, it is found that the stress difference on both sides of the weld does not exceed 10% of the maximum principal stress value. It can be approximated that the stress values of the symmetrical points on both sides of the weld without impact treatment are equal, so as to compare the stress values on both sides of the welds before and after the ultrasonic impact treatment.

3.2. Stress Test Results and Analysis before and after Ultrasonic Impact Treatment

Before and after ultrasonic impact treatment, the stress values of the weld heat affected zone under different process parameters are shown in Figure 2. The abscissa is the test group, representing different
ultrasonic impact treatment processes, and the ordinate is the residual stress value of the heat affected zone.

![Graph showing comparison of residual stress before and after UIT](image)

**Figure 2.** Comparison photograph of residual stress before and after UIT.

From figure 2, it is found that the maximum principal stress values in the heat affected zone of the plate without impact treatment are positive, that is, tensile stress, the maximum value is more than 350MPa, which is close to the yield limit. After ultrasonic impact treatment, the stress value is negative, that is, the compressive stress. This macroscopic stress-strain phenomenon can be explained by microscopic dislocation theory. The uneven heating and cooling in the welding process generate residual stress in the heat-affected zone, which is microscopically a macroscopic structure of dislocation structure, and their different arrangement and shape correspond to different macroscopic residual stress distributions. Under the action of ultrasonic peening, the surface of the heat-affected zone is plastically deformed, and the microscopic dislocation structure changes. On the stress, the tensile stress becomes small or transforms into compressive stress.

The effect of ultrasonic peening to remove residual stress can be characterized by the "reduction rate $\psi$", namely:

$$\psi = \frac{\sigma_{\text{before}} - \sigma_{\text{after}}}{\sigma_{\text{before}}} \times 100\%$$  \hspace{1cm} (1)

In the formula, $\sigma_{\text{before}}$ is the maximum principal stress before ultrasonic impact treatment, and $\sigma_{\text{after}}$ is the maximum principal stress after ultrasonic impact treatment. After ultrasonic peening with different parameters, the reduction rate of residual stress in the heat affected zone is shown in figure 3.

![Bar chart showing effects of UIT technological parameters for removal rate of residual stress](image)

**Figure 3.** Effects of UIT technological parameters for removal rate of residual stress.
From figure 3, it is found that the ultrasonic impact treatment has a good elimination effect on the residual stress of the heat affected zone of Q345 welding, and the elimination rate can reach 80%~130%. At the same time, it is found that: (1) When the impact time T is constant, the residual stress reduction rate increases with the increase of the impact current, and the decreasing rate increases with the increase of the impact current; (2) The inrush current I is constant, and when the impact time T is increased, the residual stress reduction rate does not change significantly.

As mentioned above, the reason for the residual stress reduction can be attributed to the macroscopic stress strain and the microscopic dislocation structure change. At the macroscopic point, the ultrasonic impact force acts on the surface of the welded heat affected zone and overlaps with the near surface residual stress [3, 4]. When it is greater than the yield strength of the material, plastic deformation of the surface of the material occurs, and the microscopic dislocation structure changes, resulting in a change in residual stress, namely:

$$\sigma_{\text{impact}} + \sigma_{\text{residual}} > \sigma_{0.2}$$  \hspace{1cm} (2)

In the formula, $\sigma_{\text{impact}}$ is the ultrasonic impact force, which increases with the increase of the impact current; $\sigma_{\text{residual}}$ is the residual stress; $\sigma_{0.2}$ is the yield strength of the material.

(1) When the impact time is fixed, impact force $\sigma_{\text{impact}}$ increases with the increase of impact current, also, the greater of HAZ surface plastic deformation, finally, residual stress reduction rate increases.

(2) At the same time that the surface of the weld heat affected zone is plastically deformed, the work hardening phenomenon of the material will inevitably occur, resulting in an increase in the surface micro-region yield strength $\sigma_{0.2}$. When the sum of the impact force $\sigma_{\text{impact}}$ and the residual stress $\sigma_{\text{residual}}$ is balanced with the micro-region yield strength $\sigma_{0.2}$, the surface no longer undergoes plastic deformation, and the rate of reduction of residual stress $\psi$ reaches saturation. Only when the impact current I is continuously increased and the ultrasonic impact force $\sigma_{\text{impact}}$ is increased, the equilibrium state can be broken, and the formula (2) is satisfied, plastic deformation continues to occur, and the microscopic dislocation structure changes, resulting in the residual stress continuing to decrease. However, as the degree of work hardening increases, the tendency of the residual stress reduction rate $\psi$ increases [5].

(3) When the impact current I is constant, the ultrasonic impact force $\sigma_{\text{impact}}$ is certain. With the increase of the impact time T, the plastic deformation of the surface of the welded heat affected zone is gradually stable and saturated. When the impact time T is continuously increased, it will not cause plastic deformation, microscopic dislocation structure will not change significantly, so the residual stress reduction rate $\psi$ will not change.

3.3. Analysis of the Effect of Ultrasonic Impact Treatment on Fatigue Performance

Before and after the ultrasonic impact treatment, the fatigue test results of the samples of groups A, B, C, D, E, and F are shown in table 4 and figure 4.
Table 4. Results of fatigue tests.

| Group Numbers | Sample Number | Stress Range $\Delta \sigma$ (MPa) | Cycle Times | Group Numbers | Sample Number | Stress Range $\Delta \sigma$ (MPa) | Cycle Times |
|---------------|---------------|-----------------------------------|-------------|---------------|---------------|-----------------------------------|-------------|
| A (Non-UIT)   | A1            | 171                               | 5018915     | D (Non-UIT)   | D1            | 252                               | 509500      |
|               | A2            | 180                               | 824598      |               | D2            | 260                               | 307663      |
|               | A3            | 198                               | 623244      |               | D3            | 270                               | 286731      |
|               | A4            | 207                               | 559641      |               | D4            | 288                               | 270201      |
|               | A5            | 216                               | 374112      |               | D5            | 333                               | 153669      |
| B (1.7A Impact Current) | B1            | 216                               | 791632      | E (1.7A Impact Current) | E1            | 243                               | 748766      |
|               | B2            | 225                               | 849746      |               | E2            | 260                               | 467044      |
|               | B3            | 243                               | 284861      |               | E3            | 270                               | 350359      |
|               | B4            | 252                               | 134122      |               | E4            | 288                               | 308879      |
|               | B5            | 288                               | 115842      |               | E5            | 333                               | 283495      |
| C (2.5A Impact Current) | C1            | 180                               | 525875      | F (2.5A Impact Current) | F1            | 225                               | 1648064     |
|               | C2            | 198                               | 467115      |               | F2            | 260                               | 564833      |
|               | C3            | 216                               | 401118      |               | F3            | 270                               | 458266      |
|               | C4            | 243                               | 376211      |               | F4            | 288                               | 412513      |
|               | C5            | 270                               | 153667      |               | F5            | 333                               | 355625      |

Figure 4. Relationship between stress range and cycle numbers.

From table 4 and figure 4, it is found that:

(1) Comparing the three groups of samples A, B and C (that is, the ultrasonic impact treatment of the front and back weld toes of the welded joint), the relationship between the stress range and the number of cycles, and the cycle times showed a decreasing trend with the increase of the stress range. There is no significant increase or decrease in the fatigue properties of the welded joint after ultrasonic impact treatment.

In order to find out the cause of this phenomenon, we observed the fracture of the fatigue specimen. The macroscopic shape of the typical fracture is shown in figure 5.
It is found from figure 5 that in the fatigue fracture, a large number of grooves are not fused at the root of the weld. The reason for the lack of fusion is that the welding parameters are small and the energy is insufficient when the root of the one side welding both sides formation welding is made. Un-fused in the fatigue test, it is easy to form a stress concentration phenomenon, which is the origin of the crack, and the sample is destroyed early.

2) The three sets of D, E and F samples were ultrasonically impacted on the front weld toe of the welded joint, and the back side was subjected to washing and disinfecting treatment. From figure 4, it is found that the fatigue properties of the three groups of D, E and F are better than those of the three groups A, B and C. According to the previous analysis, the damage of the fatigue specimens of the three groups A, B and C is mainly due to the un-fusion, while the D, E and F groups are milled on the back side, and the un-fused part is removed by milling. The fatigue cracks mainly originate from the weld toe.

3) Comparing the fatigue performance of D, E and F samples under different ultrasonic impact treatment parameters, it is found that when the impact current value is increased, the fatigue performance of the sample is improved, which can be explained from two aspects [6]. First, due to the increase of the impact current value, the residual stress reduction rate increases, the surface compressive stress increases, which affects the stress cycle; On the other hand, the increase of the impact current value makes the plastic deformation of the surface of the weld toe larger, which is more conducive to the formation of a smooth transition and reduce the stress concentration.

4. Conclusion

1) Ultrasonic peening cause plastic deformation on the surface of the heat affected zone of Q345 butt plate, microscopically produces dislocation structure changes, changes the stress field, and eliminates welding residual stress. The elimination rate is 80%~130%.

2) When the ultrasonic impact time is certain, increasing the impact current can improve the impact force, causing greater plastic deformation and dislocation structure changes in the weld heat affected zone, thereby increasing the residual stress reduction rate, but the tendency of the elimination rate to decrease is reduced due to the influence of work hardening.

3) When the ultrasonic peening current is constant, the impact force is constant, and the increase of the impact time has no significant effect on the elimination rate.

4) The un-fusion of the one side welding both sides formation root is the root of the fatigue crack initiation, which will cause the early damage of the fatigue specimen. The welding specification should be ensured during the welding process to prevent the occurrence of un-fusion.

5) Increasing the ultrasonic peening current value can increase the reduction rate of residual stress, and at the same time, it is beneficial to form a smooth transition at the weld toe, reduce stress concentration and improve the fatigue performance of the joint.
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