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# Effects of ultrasonic impact treatment on pre-fatigue loaded high-strength steel welded joints

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Comparative fatigue tests were conducted on as-welded, weld toe peened specimens before and after fatigue loading. Fracture surface, residual stress, microstructure and hardness were determined. The test results showed that as the pre-fatigue loading period extended, deeper cracks may have initiated and propagated and the fatigue life improvement decreased. The processes of ultrasonic peening on welded joints with existing cracks were modeled by finite element analysis. The numerical results indicated that the mechanism of UIT improving fatigue performance included two factors: compressive residual stress and the change of crack orientation. Both effects reduced as the crack became deeper.



## 1. Introduction

Ultrasonic impact treatment is a relatively new and promising technology due to its effectiveness in increasing the resistance of materials to surface-related failures, such as fatigue and stress corrosion cracking. The beneficial effects of UIT for fatigue performance of parts and welded elements have been demonstrated in previous studies [1–12]. The main reason for the improvement of fatigue strength is UIT makes use of ultrasonic vibration to impact and plastically deform the weld toe, consequently relieving of tensile residual stress and introducing compressive residual stresses into surface layers of materials. Other factors for the beneficial effect of UIT are decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of the surface layer [4,8,13,14]. Fatigue testing of welded specimens showed that UP is the most efficient improvement treatment as compared with traditional techniques such as grinding, TIG-dressing, and hamming peening [15–18].

UIT is an effective means of improving the fatigue life of structures not only in new manufacture but in maintenance and repair procedures [17]. To date, much work has focused on the fatigue strength improvement by applying UIT on new structures. However, there is also a need to investigate the effectiveness of the method for welded structures already exposed to cyclic loading conditions. Kudryavtsev et al. [19] found that the increase of fatigue strength for samples treated with UIT after fatigue loading corresponding to 50% of expected life was about 1.3 times of the ones treated before fatigue loading. The higher increase of UIT treated welded elements after fatigue loading was explained by a more beneficial redistribution of residual stresses and/or healing of fatigue damaged material. Maddox et al. [20] carried out fatigue testing on structural steel plates with longitudinal fillet welded attachments after fatigue loading which was used to represent prior service operation. They found that the weld toe fatigue cracks produced by pre-fatigue loading stopped to grow further after peening and the fatigue failure site was transferred from the weld toe to the weld root at the ends of the attachments.

The aforesaid literatures have proved that UIT can also be effective in increasing the fatigue life of structures which had undergone a period of service. But the mechanism for the improvement was not specified. This paper aimed to investigate the effects of UIT on fatigue behaviors of pre-fatigue loaded welded joints and explore the reasons by experimental and numerical method.

## 2. Testing procedure

The studies have been conducted on butt weld joints out of high strength steel S690QL. 15 mm thick plates measuring 500 mm in length have been welded by FCAW method with filler metal of FabCO XTREME 120 E121T5-G4 H4. The material properties and welding parameters are given in Tables 1 and 2, respectively. After the welding process, the plates have been sliced and

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**Table 1**
Material properties.

| Material | $\sigma_s$ (MPa) | $\sigma_b$ (MPa) | Elongation rate (%) |
|---|---|---|---|
| S690QL | 790 | 829 | 20 |
| E121T5-GC H4 | 763 | 866 | 17.8 |

**Table 2**
Welding parameters.

| Diameter of electrode (mm) | Voltage (V) | Current (A) | Welding speed (mm/min) | Interpass temperature (°C) |
|---|---|---|---|---|
| 1.6 | 220–250 | 21–24 | 190–250 | 150 |

machined to specimens, with a test cross-section of 25 times 15 mm as shown in Fig. 1.

The post-weld treatment was carried out by the half-wavelength UIT equipment invented by Tianjin University. The operating frequency of the generator was 17 kHz and the indenter consisted of a single hemispherical head pin with 3 mm diameter. The operation parameters were chosen as: a tool speed of 0.3 m/min, excitation current of 2 A and 300–400% coverage. Efforts were made to remove sharp transitions, re-entrant corners and excessive convexity and ensure the weld toe being free of the original line and obtaining a smooth uniform profile.

Fatigue tests were carried out under constant amplitude loading $\Delta\sigma$ = 250 MPa and stress ratio $R$ = 0.1 at room temperature. Fatigue specimens were divided into six groups, each of which contained 8 samples. Group A consisting of as-welded specimens was firstly tested and the expected fatigue life at a survival probability of 95% with 75% confidence level was obtained according to ISO standard [21]. For Group B to F, before carrying out the peening, each specimen was pre-fatigue loaded until the corresponding proportion of expected life was reached. To produce beach mark on the fracture surface, the applied stress range was reduced to the half range while keeping the same maximum stress for about 5000 cycles which were not taken into account when calculating the total life. The test was stopped if the fatigue life (total life) exceeded $10^7$ cycles and the specimen was regarded as run-out. The arrangements of fatigue tests are shown in Table 3.

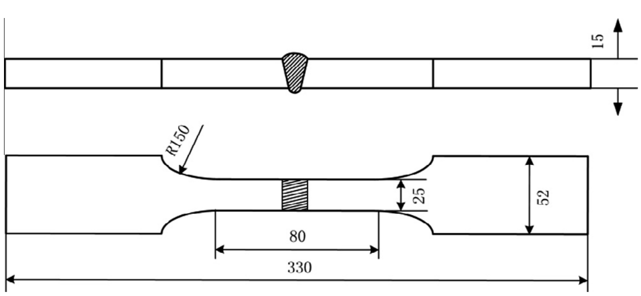


**Fig. 1.** Geometry of butt-joint specimen.

After fatigue testing, the fracture surface was observed by scanning electron microscope. To study the effect of peening and provide the basis for the finite element analysis in the subsequent section, the depth profile of residual stress in the range of 0–1.6 mm below the surface was performed by X-ray diffraction. The microstructure of the treated weld toe was observed by microscope and the indentation depth was measured. After taking photos of microstructure, the micro-hardness tests were conducted on the same etched sample with an applied force of 100 g. The hardness measurement interval was decided as 120 μm and the maximum depth is about 1.1 mm. In order to obtain lots of data within the maximum measurement depth, the hardness in the thickness direction was measured along the zigzag path which will be shown in Section 3. The test was performed in the base metal, HAZ and weld metal in such a way that the center line of measurement points is perpendicular to the surface [22].

## 3. Results

### 3.1. Fatigue life

For all the specimens with life less than $10^7$ cycles, failure occurred at weld toes. To investigate the UIT effect on different groups, the fatigue life for a given stress was derived by excluding the run-out specimens as follows [21].

Arrange the fatigue life (in logs) in ascending order, the failure probability of the $i$th specimen is:

$$P_i = \frac{i - 0.3}{n + 0.4} \tag{1}$$

where $n$ is the total number of specimen. Plot the fatigue life and failure probability in log–log coordinate. If the fatigue life follows normal distribution, the data points will show a linear relationship. The mean value $\hat{\mu}_x$ and standard deviation $\hat{\sigma}_x$ of fatigue life can be derived from the fitted line:

$$\hat{\mu}_x = \frac{x_{(10)} + x_{(90)}}{2} \tag{2}$$

$$\hat{\sigma}_x = \frac{x_{(90)} - x_{(10)}}{2.56} \tag{3}$$

where $x_{(10)}$ and $x_{(90)}$ are the fatigue life for failure probability of 10% and 90%, respectively. Then the expected life at failure probability of $P$% with confidence level of $1 - \alpha$ can be expressed by Eq. (4):

$$\hat{x}_{(P,1-\alpha)} = \hat{\mu}_X - K_{(P,1-\alpha,v)}\hat{\sigma}_X \tag{4}$$

where $k_{(P,1-\alpha,v)}$ is the one-sided error limit coefficient of normal distribution, $v$ is the degree of freedom, i.e. $n - 1$.

Fig. 2 shows the failure probability–fatigue life (total life) data for the six groups. It can be seen that each set of data basically satisfy linear relationship and the data of as-welded and 25% life + UIT are less scattered than the other four groups.

According to Fig. 2, the expected life of as-welded specimen at 95% survival probability with 75% confidence level is obtained as

**Table 3**
Fatigue tests and fatigue life.

| Group | Treatment | Number of specimens | Run-out specimen | Cycles before UIT | Fatigue life[a] ($\times 10^6$ cycles) |
|---|---|---|---|---|---|
| A | As welded | 8 | 0 | 0 | 0.245 |
| B | UIT | 8 | 2 | 0 | 3.886 |
| C | 25% life pre-fatigue + UIT | 8 | 1 | 35,166 | 2.882 |
| D | 50% life pre-fatigue + UIT | 8 | 0 | 70,332 | 1.045 |
| E | 75% life pre-fatigue + UIT | 8 | 1 | 105,498 | 0.883 |
| F | 100% life pre-fatigue + UIT | 8 | 0 | 140,665 | 0.897 |

[a] At 50% survival probability.