Effects of UIT on Microstructure and Properties of 441 Ferritic Stainless Steel Laser Welded Joint

Caiyu Zhao1a, Qiuyue Fan2b, Haoxuan Yu1c, Hao Wang1d and Desheng Xu1*
1School of Materials Science and Engineering, Jilin University, Changchun 130025, China
2Fujian Provincial Key Laboratory of Welding Quality Intelligent Evaluation, Fujian 364000, China
*Corresponding author’s email: xuds@jlu.edu.cn, azhaocy_630@163.com, bfanqiuyue1024@163.com, c2690359963@qq.com, dhaow19@mails.jlu.edu.cn

Abstract—Effects of UIT (Ultrasonic impact treatment) on the microstructure and properties of laser welded 1.5mm 441 ferritic stainless steel sheets were studied. Results indicate that the surface of the butt joint generated an ultrasonically induced strengthening layer after UIT. The average microhardness of the layer was increased by 18.1%. The tensile strength of the specimens was increased. Moreover, UIT can decrease the residual stress of welded specimens, the maximum longitudinal tensile stress in the central area was decreased by 78.4%, and the transverse residual stress was converted into compressive stress. The cupping value was increased from 34.5 mm to 37.0 mm following UIT. In addition, the fracture position was changed from the central weld to the edge weld of the cupping hemisphere. The mechanical properties were increased due to the generation of strengthening layers and the decrease of residual stress by UIT.

1. Introduction
At present, 441 ferritic stainless steel is widely used in various production fields, especially for the manufacture of welded pipes in auto exhaust systems, due to its low price, excellent formability, good high-temperature resistance, and excellent corrosion resistance[1, 2]. In the production process of the auto exhaust pipes, laser welding is one of the welding methods utilized by global manufacturers due to its high production efficiency, high energy density, and small post-weld deformation[3]. However, in the process of the pipe expanding and bending in practical production, some welded pipes will crack in the butt joint. J. C. Lippold et al.[4] found that grain coarsening, martensite formation, and high-temperature embrittlement occurred after welding. The residual stress was produced in the welded specimens of ferritic stainless steel, too. Eslam Ranjbarnodeh et al.[5] found that the decisive factor of ferrite grain growth is heat input. Tian Yaqiang et al.[6] discovered that silicate inclusions, sulfide inclusions, zirconium series shedding, and a high degree of work hardening can lead to cold bending cracking of welded pipes. S. Anttila et al.[7] evaluated the mechanical properties of ferritic stainless steel by cupping test. It is highly required of the weld drawability since the subsequent processing of auto exhaust pipes is mainly pipe expanding and bending. The cupping test method can simulate the stress condition of the specimens preferable. Jinbo Liu et al.[8] discovered that proper welding and UIT can efficiently adjust residual stress of Al-alloy welding joints. UIT can extrude and refine the nanolayer metal on the surface of the butt joint. Dislocations, lattice distortion, and grain boundary migration generated on the surface.
layer refined the grains and improved the surface plasticity under the high frequency and low amplitude impact. At the same time, the residual stress was decreased, and beneficial compressive stress appeared\cite{9,10}. Many scholars utilized UIT to improve the fatigue performance of materials, and the majority of them used UIT to enhance this performance of the medium and thick plates (more than 4 mm). It is rare to study the deformation performance of ferritic stainless steel thin sheets after UIT.

In this paper, the properties of the laser welded 1.5 mm sheets treated with UIT are related to the microstructure. After ultrasonic impacting of the laser welded sheets, the microstructures of the untreated and UIT butt joints were studied. The microhardness, tensile performance, and residual stress of the sheets were measured. The cupping values and the strain distribution were measured to study the changes of drawability after UIT.

2. Materials and methods

2.1. Materials

441 ferritic stainless steel 1.5 mm sheets were used in this experiment. The welding specimens had a dimension of 180 mm × 90 mm, and the cupping specimens had a diameter of 180 mm. Table 1 shows the nominal and the actual chemical composition of 441 ferritic stainless steel. The actual chemical composition was tested by benchtop spectrometer (Q4 TASMAN) and meets the standard.

| Chemical element (wt.%) | C  | Si  | Mn  | P  | S  | Cr     | Nb | Ti  | N  |
|------------------------|----|-----|-----|----|----|--------|----|-----|----|
| 022Cr18NbTi (GBT3280-2007) | ≤0.03 | ≤1.0 | ≤1.0 | ≤0.04 | ≤0.015 | 17.5—18.5 | ≥3×C+0.3 | 0.1—0.6 | -  |
| 441                    | 0.014 | 0.169 | 0.228 | 0.012 | 0.001 | 17.52  | 0.429 | 0.286 | 0.0076 |

2.2. Methods

A wire electric discharge machine (DK7732) was used to cut some of the 1.5 mm sheets into welding specimens of 90 mm × 90 mm dimensions. Then all welding specimens were cleaned before welding. The welding specimens were butt welded in the rolling direction with type I groove. German IPG YLR-2000 laser welding machine was the equipment used in the welding with the welding process parameters being a power of 1.3 KW, a welding speed of 25 mm/s, and a defocusing amount of 0mm. There were two groups of welded specimens: untreated specimens and UIT specimens. The UIT-125 ultrasonic impact machine used in UIT had a processing frequency of 17.68 kHz, a current of 0.50 A, an amplitude of 6.0 μm, and a pulse width of 10%. The diameter of the single impact needle was 5 mm. The UIT processing speed was 15mm²/min. The UIT processing method was a full-coverage treatment centered on the weld with the front and back sides 20 min each. Fig 1 shows the equipment used in UIT and schematic diagram of the UIT process. The fiber laser marking machine (ZK-20W-GA) was applied to ablate 2 mm interval and 1 mm diameter unit points on the surface of the cupping specimens with a laser power of 20 W, and a marking speed of 100 mm/s.

![Figure 1. Equipment used in UIT (a) and schematic diagram of the UIT process (b).](image_url)
An optical microscope (Axio Scope A1) was applied to obtain the metallographic images of the butt joints before and after UIT. The Vickers microhardness of the butt joints was measured by microhardness tester (HVD-1000MP) with a load of 0.2 kg and a duration of 15 s. A universal testing machine (WDW-200) was used to evaluate the tensile properties of the specimens before and after UIT with a tensile speed of 5 mm/min. The dynamic and static strain test system (JM3841) was applied to conduct stress tests and analysis through the small hole method. The EC400 sheet metal forming test machine was used to carry out the cupping test with a punch moving speed of 0.3 mm/s. The ARGUS optical strain measuring instrument was used to establish tridimensional models of cupping specimens to measure and analyze the strain distribution.

3. Results and discussions

3.1. Microstructure

The microstructures of the butt joints of the welded specimens before and after UIT are shown in Fig 2. The grain size of two base metal microstructures in Fig 2 (a) II and (b) II was measured to be grade 6, and the average grain size was 45 μm.

Compared with other welding methods such as TIG, laser beam energy density in the welding is very high, its heat input range is limited. The laser weld cooled rapidly with the use of small power and rapid welding so that the butt joint width was small. Fig 2 shows the roughly same weld microstructures of the butt joints before and after UIT. These microstructures contained fine central equiaxed crystals, coarse columnar crystals, almost invisible HAZ, and base metal grains. These led to the uneven distribution of microstructures. In Fig 2, the internal structures after welding were stable single-phase ferrite rather than martensite because of the thin thickness and the fast cooling rate. The ferrite microstructure cannot undergo phase transformation during heating and cooling, so the coarse ferrite grains cannot refine by heat treatment[12].

![Figure 2. The butt joint microstructures of untreated specimen (a) and UIT specimen (b).](image)

The surface roughness of specimens changed after UIT, resulting in smooth microgrooves[8]. Fig 2 (b) III shows a slight concave deformation at the edge of the microstructure, and the internal microstructure did not change. The smooth grooves generated on the treated surface were small since an ultrasonic shock amplitude of 6 μm. Y. Yu[13] discovered that the width of the observable plastic deformation layer of S50C steel after UIT reached 20 μm. Yingxia Yu[14] found that the plastic deformation layer depth of 16MnR steel after UIT was 80 μm. The plastic deformation layers were visible in other metals such as austenitic and duplex stainless steel after UIT[15]. There were a few dents
on the sample surface and no apparent deformed layer as other metals in Fig 2 (b) because the compression refinement in ferrite structure after UIT was different from the crushing refinement of austenite grains\cite{15}.

3.2. Microhardness

The microhardness test results with the test point diagrams are shown in Fig 3. In Fig 3 (a), the test points of the UIT surface layer and WJ (welded joint) surface layer were 100 $\mu$m away from the surface. The test points of UIT and WJ were the central part of the thickness direction of the specimens. Fig 3 (b) shows the microhardness results in the thickness direction of the base metal.

Fig 3 (a) shows a trend of the microhardness distributions: low on both sides and high in the middle. Combined with Fig 2, the brittleness and hardness were increased at the butt joint with the grew columnar grains. The weld center was a petty and uniform equiaxed crystal structure more than the base metal, which has the effect of grain refinement and the highest hardness\cite{17}.

In Fig 3, the overall microhardness of the surface layer after UIT was increased by 18.1%. Fig 3 (a) shows that the total hardness of the sample UIT surface layer was the highest, and there was no significant difference in others. In Fig 3 (b), the microhardness of the UIT base metal surface layer was above 190 HV. There was no significant difference in microhardness between the two groups in the thickness direction except for the UIT surface layer. Nano-scale grain strengthening occurred during ultrasonic high frequent extrusion on the surface layer ferrite grains. The strengthening influence depth reached at least 100 $\mu$m. Relevant studies demonstrated that UIT induced dislocation aggregation in the surface layer grains. The dislocation density increased when UIT continued. It resulted in the formation of many tiny dislocation cells and sub-grains with shrinking size. These cells and grains were subdivided into polygonal sub-micron grains and eventually decomposed into nanocrystals\cite{14, 16}. Fig 2 and Fig 3 indicate that the UIT strengthening effect in the test was limited to the surface layer, and did not affect the internal structure and microhardness.

Figure 3. Microhardness curves in cross section of welded specimens (a) and in the thickness direction of base metal (b) before and after UIT.

3.3. Room temperature tensile test

Table 2 presents the results of room temperature tensile test. Fig 4 shows engineering stress-strain curves of tensile test and tensile specimens. In Fig 4, BM-UIT is a tensile specimen with an overall coverage of UIT.
Table 2. The results of room temperature tensile test.

| Specimen | Tensile strength /$\delta_b$(MPa) | Elongation /$\delta_u$ |
|----------|----------------------------------|------------------------|
|          | A                  | B       | C        | A           | B           | C           | Average |
| BM       | 445.94             | 447.69  | 445.88   | 446.50      | 38%         | 37%         | 38%      |
| BM-UIT   | 455.74             | 454.78  | 454.69   | 455.07      | 36%         | 36%         | 35%      |
| WJ       | 432.42             | 434.30  | 437.32   | 434.68      | 30%         | 30%         | 32%      |
| WJ-UIT   | 446.71             | 448.51  | 448.1    | 447.77      | 30%         | 33%         | 31%      |

Fig 4 shows that all welded specimens cracked in the base metal with consistent fracture sites with visible necking phenomenon. All curves in Fig 4 have no platform yield phenomenon. The higher the hardness, the greater the strength of the metal[22]. Combined with Table 2, the strength and elongation of the WJ reduced significantly in contrast with the BM. The strength of the UIT specimens was improved, and the elongation of the BM-UIT decreased by 6%. In addition, the tensile strength of the WJ-UIT was comparable to BM, and the elongation of the WJ-UIT did not change conspicuously. The strength and hardness increased due to a nano-strengthening layer on the surface of welded specimens induced by UIT. The elongation was not weakened after UIT since the particularity of the butt joint.

3.4. Residual stress
Fig 5 shows the stress test results measured by the small hole method. $\sigma_1$ is the longitudinal residual stress along the weld direction, $\sigma_2$ is the transverse residual stress perpendicular to the weld direction.
The residual stress will occur after welding due to the welding of materials is a process of uneven heating and cooling. It will even cause deformation when residual stress is large\cite{18}. The welded specimen was easier to reach the ultimate fracture when the residual stress was superimposed with the external force. The stress measured by the small hole method was layered local residual stress in thick plates, so the compressive stress layer induced by UIT can be measured\cite{11, 19, 20}. Compressive stress was also introduced into the surface layer of the 1.5mm thin sheets in the test due to the surface characteristics of UIT. Since the thickness was small, the measured stress after full penetration was the average residual stress of the specimens. Fig 5 shows that the $\sigma_1$ and $\sigma_2$ of welded specimens were diminished greatly after UIT. The maximum longitudinal tensile stress in the central area was decreased by 78.4%, and the transverse residual stress was converted into compressive stress.

### 3.5. Cupping test and strain analysis

Table 3 presents the results of the cupping test. The tensile load-displacement curves of the cupping specimens and the cupping specimens are shown in Fig 6.

Fig 6 (b) shows two types of cracks of the cupping specimens. One is the longitudinal crack propagating along the weld, and the other is the transverse crack perpendicular to the weld. The drawability of the welded specimens in Fig 6 (a) reduced seriously due to the uneven distribution of the microstructures and the influence of the residual stress. The cupping value and tensile force of the UIT improved significantly. Combined with Table 3, the cupping value was increased from 34.5 mm to 37.0 mm following UIT. UIT has the assured potential to enhance the drawability of the material.

| Specimen | Cupping value /mm | Maximum tensile force /KN |
|----------|-------------------|---------------------------|
| BM       | 42.5              | 154.7                     |
| WJ       | 34.5              | 127.5                     |
| UIT      | 37.0              | 138.0                     |

ARGUS optical strain measurement equipment was applied to photograph the cupping specimen to establish the model and measure its strain distribution. Fig 7 shows the strain distribution nephogram of the cupping specimens. Table 4 presents the point data of thickness reduction obtained according to the various regions shown in Fig 7. The FLD diagram and sheet forming state diagram obtained by taking the major and minor strains as the transverse and longitudinal coordinates are shown in Fig 8\cite{21}.

The distribution of major strain and thickness reduction in Fig 7 can reflect the macroscopic morphology of the crack zone. The values of major strain and thickness reduction increased obviously in the fracture zone. The crack initiation source can be precisely located, for the maximum value was measured at the crack initiation point. The butt joint in the minor strain distribution map divided the whole sample into two parts, and the strain in this area decreased generally. Fig 7 shows that the butt
joint hindered the deformation in the minor strain direction. In Fig 8, the major and minor strains were conformed to the numerical relationship of the bulging zone in the sheet forming the limit diagram. The major and minor strain distribution became a scattered point distribution, and the values increased sharply after reaching the fracture boundary. The values were up to the limit at the crack initiation point. In Table 4, the thickness reduction of each region of UIT was generally higher than WJ.

In Fig 7, the crack from the UIT was similar to WJ, and both were transverse cracks perpendicular to the weld direction. From Fig 5, the residual stress of WJ was the largest at the center of the long weld. The weld reached the fracture limit faster due to the residual stress superimposed with external force. Since the residual stress of the specimen was decreased and the surface layer of the impacted area was induced nano-fine grain strengthening after UIT, it can withstand a higher tensile load and attain more deformation in the process of strain under force.

Figure 7. Nephogram of major strain, minor strain and thickness reduction distribution.

Table 4. Thickness reduction rate data.

| Region | Fault zone | Edge | Safety zone | Max |
|--------|------------|------|-------------|-----|
| BM (%) | 72.9       | 57.1 | 60.7        | 53.4| 48.4 | 47.9 | 43.9 | 73.4 |
| WJ (%) | 63.3       | 49.0 | 47.9        | 48.4| 34.7 | 39.2 | 36.9 | 63.3 |
| UIT (%)| 63.4       | 50.6 | 48.2        | 46.2| 40.2 | 34.3 | 41.9 | 63.4 |
The residual stress of the welded specimen was reduced, and the ferrite grains in the surface layer were extruded and strengthened after UIT. A work-hardening effect was caused by micro deformation, which improved the strength and hardness of the surface layer.

4. Conclusions
Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The surface of the butt joint generated an ultrasonically induced strengthening layer after UIT. The average microhardness of the layer was increased by 18.1%. The tensile strength of the specimens was increased.

(2) UIT can decrease the residual stress of welded specimens, the maximum longitudinal tensile stress in the central area was decreased by 78.4%, and the transverse residual stress was converted into compressive stress.

(3) The cupping value was increased from 34.5 mm to 37.0 mm following UIT. The fracture position was changed from the central weld to the edge weld of the cupping hemisphere.

(4) The mechanical properties were increased due to the generation of strengthening layers and the decrease of residual stress by UIT.

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