Inter-pass ultrasonic impact treatment (UIT) of welds

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by

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Two years’ study at TU Delft almost comes to an end. During this period, I have learned and experienced a lot more than I can describe. The tensing exam periods, the everlasting friendship and the inculcations, all become an impressive memory in my mind. Hereby, I would like to thank everyone who has accompanied me for the past two years.

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The objective of this project is to investigate the feasibility of the inter-pass ultrasonic impact treatment (UIT) of welds. It is desirable to apply UIT after welding to redistribute the residual stresses, to reduce the welding distortion, to modify microstructures and to improve the mechanical properties of the welding plates.

In this project, a thermal model was built up based on the Goldak’s double-ellipsoidal heat source model and further validated to determine the temperatures of the weld bead after a certain period of time. UIT was applied to the 4 mm-thick plates after the single-pass welding at different temperatures. Digital image correlation results show that distortion was reduced when UIT was applied and it was further reduced when the treating temperature is at around 660°C.

UIT was also carried out for the 8 mm-thick plates after the first-pass welding at different temperatures. Microscopy shows that UIT induced severe plastic deformation, resulting in microstructure modifications, such as grain refinement and pancake structures. Micro-hardness of the top surface with UIT was increased. When UIT was applied at around 653°C, the peak hardness became a little smaller than that with UIT at room temperature. A second weld was applied to the 8 mm-thick plates after inter-pass UIT. However, welding distortion, microscopy and micro-hardness do not show any improvement by inter-pass UIT. Contour mapping method was applied for the residual stresses measurement. Due to the limitation of the wire electrical discharge machining (EDM) and surface profile measurement, the residual stresses measurement was not successful. The Charpy V-notch tests show that the ductile-to-brittle transition temperature (DBTT) was lowered with inter-pass UIT at room temperature and further lowered with inter-pass UIT at a higher temperature (around 653°C).
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Introduction

Ultrasonic impact treatment (UIT) is a relatively novel technology focusing on life extension of assets by improving the fatigue properties of materials [1]. The primary application has been the improvement of weld structures. The application of UIT improves the properties of welded and base material structure by introducing compressive residual stresses, changing the weld toe geometry, and modifying grain structures. The application of the UIT process assists in extending the life of existing structures and newly manufactured components.

The role of UIT after multi-pass welding of high strength steels on stress relaxation, stress concentration factor and metallurgy has been investigated. However, the effect of the treatment between welding passes on the evolution of mechanical properties such as micro-hardness and distortion is still lacking. The effect of inter-pass UIT temperature is of great interest. With different treating temperatures, the treating phases may vary from austenite to ferrite or bainite, which have a different plastic deformation behaviour. So the purpose of this project is to investigate the feasibility of inter-pass UIT and temperature effect of the inter-pass UIT and the effects of UIT applied between welding passes on the evolution of microstructures, distortion of the welding plates and mechanical properties.

1.1. Research objective

The objective of this project is to investigate the evolution of microstructure modifications, welding distortion, residual stresses and mechanical properties due to the inter-pass UIT applied between welding passes. The list of tasks in this project is listed below:

- Design of the UIT holder to achieve different treating temperatures and angles.
• Investigating the microstructure modifications due to inter-pass UIT.
• Welding distortion measurements of as-welded and UIT treated plates.
• Residual stresses measurements of as-welded and UIT treated plates.
• Investigating the hardness change and mechanical properties due to inter-pass UIT.
• Investigating the ductile-to-brittle transition temperature due to inter-pass UIT.

1.2. Thesis outline
In this thesis, chapter 2 will provide the background of this project. The working mechanism and effect of UIT will be discussed. Then, the concept of welding distortion and welding residual stresses will be introduced. The measurement of welding distortion will be carried out with the help of digital image correlation (DIC) and contour mapping method is applied to measure the longitudinal residual stress along the cross-section. Furthermore, at the plane perpendicular to the weld, techniques to characterise microscopy and micro-hardness will be introduced. Charpy V-notch impact test will also be introduced.

The experimental part is introduced in chapter 3 with the measurement of cooling curves and the validation of thermal model of the 8 mm-thick welding plates. The validated thermal model will provide the information related to time and temperatures, which is useful in the ultrasonic impact treatment part. Then, the UIT will be applied to the welding plates at different temperatures and angles with the help of a special holder. Welding distortion will be measured by DIC and residual stresses will be measured by contour mapping method, respectively. Then, the microstructures and hardness will be obtained by optical microscopy and Vicker’s hardness testing equipment. Finally, sub-size Charpy V-notch impact tests are performed to obtain the absorbed energy before fracture at various temperatures.

Chapter 4 will provide the results of welding distortion, residual stresses distribution, microscopy, hardness measurements and Charpy V-notch tests.

Chapter 5 will present the discussion of the experimental results, which are related to the mentioned literatures.

Chapter 6 will draw a general conclusion and further improvement with recommendations will also be presented.
After welding, welding distortion and residual stresses are likely to be present in the components. Therefore, post weld treatments such as UIT are applied to relieve the distortion and change the stresses distribution. DIC is a full-field and non-destructive method to detect the out-of-plane displacement of welding plates. As for the residual stresses, centre hold drilling (CHD) is only effective for near-surface residual stresses and X-ray diffraction (XRD) cannot detect through-thickness residual stresses either. Therefore, the contour mapping method is an alternative for mapping the longitudinal residual stress inside a cross-section when the neutron diffraction or high-energy XRD is not available. Finally, microstructures and hardness can be obtained by means of optical microscopy and hardness testing equipment. In this chapter, basic knowledge related to UIT and characterisation techniques in terms of welding distortion, residual stress, microscopy, hardness and fracture resistance will be discussed.

2.1. Ultrasonic impact treatment

Ultrasonic impact treatment is a technology developed by Statnikov and his team in the early 1970s in Soviet Union, which was initially used to strengthen the hulls of nuclear submarines [1]. The development of this technology in the late 1990s and early 2000s resulted in the Esonix equipment which was developed by Applied Ultrasonics [2]. Nowadays, UIT is applied to weld toes to improve weld toe profiles and surface and to induce compressive residual stress [3, 4]. Furthermore, the fatigue and corrosion resistance as well as the abrasion resistance are also increased [5].
2.1.1. **UIT mechanism and system**

UIT is based on instrumental conversion of harmonic oscillations of the ultrasonic transducer into the pulses of force at the treated surface [6]. Usually, a UIT system starts with an ultrasonic transducer, converting the ultrasonic impulse (the ultrasonic frequency in the undertaken experiments is set as 27 kHz) into the electrical impulse. By applying the magnetostrictive transducer, the electrical energy is converted into the mechanical vibration which is further amplified by passing through a waveguide. Finally, some free-floating pins are installed at the end of the waveguide in order to transfer the energy from the waveguide to the treated surface more effectively. A schematic of the system is shown in figure 2.1.

![Figure 2.1: Schematic diagram of the Esonix UIT system (1 — magnetostrictive transducer, 2 — waveguide, 3 — indenter, 4 — treated surface, I — ultrasonic oscillations, II — impact impulses) [7].](image)

UIT introduces high-power ultrasonic oscillations and waves directly into the material through pins, positively affecting the material structures, conditions, and properties and thus resulting in a significant increase in fatigue life.

2.1.2. **Control parameters**

Based on the UIT system shown in figure 2.1, the control parameters of UIT are considered as ultrasonic frequencies, treating speeds, pin diameters, treating passes and treating angles.

The ultrasonic frequency combined with the input power provides the oscillation amplitude and further determine the impact frequency of the pins. The Esonix UIT system provides four levels of ultrasonic frequencies, namely 27, 36, 44 and 55 kHz and each frequency corresponds to a specific hand tool size, which are shown in figure 2.2.
2.1. Ultrasonic impact treatment

The treating speed mainly affects the treating efficiency. A lower treating speed increases the contact time per unit length between the pins and treating surface, which improves the treating efficiency. However, too high a treating speed causes a reduction of fatigue performance and treatment intensity. As can be seen in figure 2.3, with a preset amplitude of the ultrasound displacement of 30 µm \(^{[8]}\), the residual stress distribution as a function of depth in the workpiece varies with the treating speeds.

Similarly, the number of treating passes also influences the treating efficiency by changing the contact time per unit length between the pins and treating surface. With an increasing number of treating passes, the compressive stress is increased. However, additional passes may damage the weld toe by deepening the groove and causing materials to flake off \(^{[9]}\). According to Statnikov et al. \(^{[10]}\), the maximum number of passes is usually not more than four to achieve the desirable result.

The produced weld toe radius depends on the pin diameters. With an increasing pin diameter,
the weld toe radius increases with a wider field of compressive residual stresses but a lower magnitude [11]. On the contrary, a small pin diameter leads to a deeper indent and less wider field of compressive residual stress. Normally, the pin diameter is 3 mm to obtain a smooth transition zone.

The treating angle determines the resolved forces. With an treating angle vertical to the weld toe, the normal force is maximum and therefore more compressive stress is built up under the weld toe. According to Applied Ultrasonics [12], the working angle should be between 30° and 60° for a T-joint weld, which is shown in figure 2.4.

![Figure 2.4: Impacted angles for proper treatment.](image)

2.1.3. Effect of UIT

The effect of UIT is quite evident when the treated weld toe is inspected. As can be seen in figure 2.5, the treated weld toe is very smooth and the weld toe radius is increased compared with the as-welded condition. However, UIT also introduces a slight undercut at the weld toe. More details about the weld toe geometry after UIT can be found in figure 2.6.
2.1. Ultrasonic impact treatment

Figure 2.5: The view of the butt welds in as-welded condition (left side sample) and after application of UIT (right side sample). Notice the formation of a uniform, shiny groove along the weld toe marked with arrows and shown in greater details in the insert [13].

Figure 2.6: Profile of the weld toe improved by UIT [14].

Different physical zones of a treated metal are demonstrated in figure 2.7. The UIT process is accompanied with a quick local heating of the material in the ultrasonic impact point and a quick heat removal from the area. In addition, intense plastic deformation occurs in this area, which is about 0.02-0.1 mm deep. The combination of the above conditions produces a material with new properties that appears on metallographic pictures as a “white layer” (figure 2.8), which is not apt to etching. This material has no structure and is characterised by a high contact strength and corrosion resistance [2]. Subsequently, a plastic deformation zone which is about 1-1.5 mm in depth can be distinguished. In this zone, the cyclic endurance,
compensation of deformation and corrosion-fatigue strength are improved. In the impulse relaxation zone (3-5 mm), a reduction in residual stresses and strains up to 70% of the initial state are found. In the ultrasound relaxation zone, the effect is similar, only with a lower reduction, up to 50%.

In conclusion, UIT creates a favourable compressive stress in the treated zone; resulting in

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**Figure 2.7**: Physical zones of UIT effect on material properties and condition [8].

<table>
<thead>
<tr>
<th>ZONES</th>
<th>TECHNICAL EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;White layer&quot;</td>
<td>Wear-resistance, corrosion resistance</td>
</tr>
<tr>
<td>Plastic deformation</td>
<td>Cyclic endurance, compensation of deformation, corrosion-fatigue strength</td>
</tr>
<tr>
<td>Impulse relaxation</td>
<td>Reduction in residual welding stress and strain of up to 70% of the initial state</td>
</tr>
<tr>
<td>Ultrasonic relaxation</td>
<td>Reduction in residual welding stress and strain of up to 50% of the initial state</td>
</tr>
</tbody>
</table>

**Figure 2.8**: White layer in the UIT zone, marked by the yellow arrow [2].

---
2.2. Welding distortion and residual stress

Welding distortion is caused by residual stresses. When the heated weld region contracts non-uniformly, shrinkage in one part of a weld exerts eccentric forces on the weld cross-section, causing plastic deformations. Detectable distortion occurs as a result of this nonuniform strain [15].

One novel way to detect welding distortion is DIC. DIC is a full-field image analysis method, which can determine the contour and the displacement of a plate in three dimensions [16]. For the measurement of residual stresses near the surface, CHD is an appropriate method. Moreover, contour mapping is a method to determine the residual stresses distribution over a cross-section.

2.2.1. Welding distortion

The distortion of welded components can be divided into three categories: (1) transverse shrinkage occurring perpendicular to the weld line, (2) longitudinal shrinkage occurring parallel to the weld line and (3) angular distortion involving the rotation around the weld line. These three types of distortion are depicted in figure 2.9. In this study, only the angular distortion (out-of-plane distortion) of a butt weld is of interest.

Angular distortion often occurs in butt weld joints when transverse shrinkage is not uniform in the thickness direction. Usually, the angular distortion of a multi-pass welding is more severe due to the accumulated angular distortion [17].

Figure 2.9: Fundamental dimensional changes that occur in weldments: (a) transverse shrinkage in a butt joint, (b) longitudinal shrinkage in a butt joint and (c) angular change in a butt joint [17].
2.2.2. Digital image correlation

Based on stereovision, 3D-DIC uses two cameras to capture the picture of the measured object. By comparing a reference image with an image of the deformed state of the object, the deformation is given in three dimensions. Speckle patterns (white and black) are evenly applied on the welding plate. The stereo correlation between the images of the left and right camera allows the measurement of the geometry and the position of the plate [18]. A typical Limess Q-400 DIC system is shown in figure 2.10.

![Figure 2.10: A limess 3D digital image correlation system Q-400 [19].](image)

In figure 2.11, the DIC measurement of the out-of-plane deformation of the conventional welding and welding with additional heating is shown. The benefit of DIC is that it has an accuracy of $50 \mu m$ and provides a full-field image analysis.

![Figure 2.11: The out-of-plane deformation measured by DIC of AISI-316L plate (a) with conventional welding and (b) welding with additional heating [16].](image)
2.2. Welding distortion and residual stress

2.2.3. Centre hole drilling

During welding, metals undergo localised heating which causes the non-uniform temperature distribution in the weld. As the weld pool solidifies and shrinks, it begins to exert stresses on the surrounding metals. Meanwhile, the constraining effect of a clamping system also affects the residual stresses. CHD is a kind of semi-destructive residual stress measurement method based on the stress relaxation. The CHD equipment is illustrated in figure 2.12.

Figure 2.12: The centre hole drilling equipment [20].

Centre hole-drilling method requires drilling a small hole, typically 1-4 mm in diameter, to a depth approximately equal to its diameter. A specialised three-element rosette, which is shown in figure 2.13a, measures the surface strain relief in the material around the hole [21]. A typical gage rosette for residual stresses measurements near welds is shown in figure 2.13b. Beaney [22] estimated that the error in residual stress measurement by CHD in steel is around 8%. However, when the residual stresses are beyond 60% of the yield strength, the error level increases due to local plasticity of the hole. Another drawback of CHD is that it can only measure near-surface residual stresses, which restricts its usage for thick specimens.

Figure 2.13: Residual stress gage rosettes (a) for a normal type and (b) for a weld [20].

According to Gao [1], the near-surface longitudinal and transverse residual stress obtained from CHD of UIT treated plates under the weld toe become more compressive compared to that of as-welded plates (figure 2.14).
2.2.4. Contour mapping method

Contour mapping method is a relatively new method to measure the residual stresses in many applications. Compared with traditional stress measurements, the contour mapping method is able to provide a 2-D stress map over a full cross-section. As for the traditional residual stresses measurement methods, the XRD method is limited by the specimen size, about 50 mm with a minimum spatial resolution of 1 mm [23]. CHD method is only effective for the near-surface residual stress with a 1-D dimension. In order to inspect the residual stress effect by UIT of a welding plate with a dimension of $250 \times 200 \times 8$ mm, XRD and CHD methods seem to be less suitable.

Contour mapping method [24] is based on the Bueckner’s superposition principle [25]. The superposition principle assumes elastic relaxation of the material and the cutting of the sample does not introduce additional stresses that could affect the original stresses present in the component (figure 2.15).
As can be seen in figure 2.15, the residual stresses are present in A and remains undisturbed. When A is cut into two parts, without introducing considerable stresses, due to stress relaxation, both parts deform. In C, the free surface created via cutting is forced back to its original flat position, indicated by the arrows in figure 2.15 C. With the elastic deformation assumption, the original residual stresses are calculated.

\[ \sigma^{(A)} = \sigma^{(B)} + \sigma^{(C)} \]  

(2.1)

When the wire electrical discharge machining (EDM) is applied to the specimen, it introduces very small stresses [23]. Additionally, firmly restrain of the sample during cutting improves the accuracy the contour results. A schematic of the wire EDM machine can be found in figure 2.16a. In order to achieve precision surfaces with low roughness, a skim cut is applied to the specimen [27]. After wire EDM, the surface contour needs to be measured either with a coordinate measuring machine (CMM) [24] or a lase scanner [28]. Then, the data is numerically processed and aligned from the two halves of the cutting part. Smoothing the data and evaluating the smoothed surface at the location of the nodes are carried out in the finite element mesh [28, 29]. As can be seen in figure 2.16b, the averaged contour data of a welding plate is measured.
After the smoothing of the contour data, the deformed surface is forced back to its original flat position. Assuming an elastic behaviour, the residual stresses can be calculated. In figure 2.17a, the calculated residual stresses of a welded plate by contour mapping can be found. In figure 2.17b, comparison between different residual stresses measurement is illustrated, indicating that the contour mapping method is powerful to provide information accurate enough for residual stresses analysis. However, the accuracy of contour mapping method depends on the accuracy of wire EDM, the measurement of the surface contour, data processing and boundary conditions applied in the finite element model.
2.3. Microstructures and micro-hardness

Microstructures of the weld with UIT are modified compared to the as-welded condition. UIT results in a significant grain size refinement and the orientation of the treated grains become less random. The change of microstructures further improves the mechanical properties of the weld, such as hardness and fatigue life.

2.3.1. Microstructure modification

According to Dutta [32], the high-frequency treatment causes dynamic recrystallisation on the top surface of the weld. The heavy deformation results in the apparent recrystallisation as ultra-fine grained ferrite, thereby improving the ductility of the heat affect zone (HAZ). As can be seen in figure 2.18, the weld toe becomes smoother after treatment and the grain size and orientation change in the HAZ of the weld. Furthermore, as can be seen in figure 2.19, the untreated grains are large and with random orientation, while the treated grains are denser with a more uniform orientation.
2.2. Background

Figure 2.18: The weld toe geometry and HAZ of an untreated weld toe and a treated weld toe [33]. The treated weld toe is smoother.

Figure 2.19: The microstructure of an untreated weld toe and a treated weld toe [33]. The treated microstructures contain smaller grains with uniform orientations.

2.3.2. Micro-hardness

Hardness is an important mechanical property when judging the quality and possible applications of a material. It can also give indications concerning the tensile strength, ductility, or wear resistance of a material:

\[
\text{Hardness} = \frac{\text{Test Force}}{\text{Indentation Size}} \tag{2.2}
\]

In Vickers hardness test, the indenter is a regular four-sided diamond pyramid with an interfacial angle, \( \alpha \), of 136°, which is shown in figure 2.20. Vickers hardness can also be calculated with the following formula [34]:

\[
HV = 0.102 \frac{F}{A} \tag{2.3}
\]

\[
A = \frac{d^2}{2 \sin(136^\circ/2)} = \frac{d^2}{1.854} \tag{2.4}
\]

\[
HV = 0.1891 \frac{F}{d^2} \tag{2.5}
\]

with \( F \): the force applied, and \( d \): the mean diagonal length of the indentation.
2.3. Microstructures and micro-hardness

According to Dutta [32], the micro-hardness of the fusion zone is significantly lower than that in the heat affected zone. However, after UIT, the micro-hardness of the fusion zone increases and the hardness gradient across the fusion line decreases. The local hardness distribution at the welding toe can be seen in figure 2.21.

Figure 2.21: Micro-hardness indentation at the welding toe (a) before (b) after UIT and micro-hardness contour maps (c) before (d) after UIT [32].
2.4. Charpy V-notch impact test

This part is removed due to confidentiality.
2.5. UIT at different temperatures

If UIT is applied to steels after welding at room temperature, then the treated phase is likely to be ferrite with carbide; however if treated at an intermediate temperature (500 °C), then recrystallisation may initiate; if treated at an even higher temperature (800 °C), then the treated phase probably is austenite. UIT introduces severe plastic deformations and therefore treating the weld at various temperatures (different phases of iron) is likely to produce different mechanical properties with different deformation behaviours.

According to Li et al. [41], for an iron-base alloy, the deformation is inhomogeneous at a low temperature, restricted to a few slip bands and no twins are formed; at a higher temperature, a more homogeneous distribution of dislocations are observed and twins form above 500 °C [42]; at temperature above 700 °C, new grains form and grain boundary ledge can easily be the sources of dislocations and twins [42, 43].

2.6. Conclusion

High strength steels have been widely used in industry such as heavy-load constructions. However, after welding, there are residual stresses present, which do harm to the workpiece. UIT is a technique to introduce compressive stress, decreasing tensile residual stress and alleviating welding distortion. In the meantime, the weld toe geometry, microstructures and mechanical property are modified after treatment.

Digital image correlation is a novel method to measure the full-field out-of-plane distortion after welding with a fairly high accuracy. Contour mapping method is effective in measuring the residual stresses (uni-axial) over a cross-section. For the micro-hardness measurement, Vickers hardness test is effective to measure the hardness distribution among the weld toe, which is an indication of the mechanical behaviour. Charpy V-notch impact test is useful to characterise the fracture resistance of a material.
Experimental procedures

The material used in these experiments is S700MC, which is a high-strength steel. 4 mm-thick plates were prepared for single-pass welding and 8 mm-thick plates were used for two-passes welding. Gas metal arc welding (GMAW) with modified welding parameters was applied. Subsequently, the thermal filed model was built up and UIT was carried out at different treating temperatures and angles. Finally, characterisations in terms of welding distortion, residual stress, microstructures, hardness and fracture resistance were explored by DIC, contour mapping, optical microscopy, hardness test and Charpy V-notch impact test, respectively.

3.1. Welding experiment

3.1.1. Base material
The base material selected is S700MC, which is a hot-rolled, high-strength low-alloy steel with a yield strength of 1034 MPa [44]. With such a high yield strength, this high-strength steel is extensively used as heavy load and heavy construction applications. It also delivers desirable weldability for fast and efficient processing. The chemical composition of S700MC can be found in table 3.1 and other mechanical and physical properties can be found in table 3.2.
Table 3.1: The average chemical composition of S700MC [45]

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>B</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt.%</td>
<td>0.049</td>
<td>0.109</td>
<td>1.934</td>
<td>0.009</td>
<td>0.001</td>
<td>0.041</td>
<td>0.0001</td>
<td>0.017</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Mo</th>
<th>N</th>
<th>Nb</th>
<th>Ni</th>
<th>Ti</th>
<th>V</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt.%</td>
<td>0.011</td>
<td>0.004</td>
<td>0.0049</td>
<td>0.068</td>
<td>0.019</td>
<td>0.121</td>
<td>0.007</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 3.2: Other properties of S700MC steel [44]

<table>
<thead>
<tr>
<th>Density (g cm(^{-3}))</th>
<th>Possion’s ratio (25 °C)</th>
<th>Elastic modulus (GPa)</th>
<th>Thermal expansion (25 °C)</th>
<th>Melting point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7-8.03</td>
<td>0.27-0.30</td>
<td>190-210</td>
<td>16-17</td>
<td>1370-1400</td>
</tr>
</tbody>
</table>

Figure 3.1 shows the microstructure of S700MC steel. The base metal is characterised by fine-grain ferrite with segregation shearing lines, expanding along the plate rolling direction as a result of inhomogeneous plastic deformation [46]. The average hardness of the base metal is \( H_{\text{V_{0.5kgf}}} = 260 \pm 10 \).

![Figure 3.1: Microstructure of S700MC steel.](image)

3.1.2. Gas metal arc welding

GMAW is a type of arc welding using a consumable filler wire, incorporated with shielding from externally shielding gases [15]. The process is schematically depicted in figure 3.2. Due to its numerous advantages, GMAW is widely used. The welding machine used sustains a constant
3.1. Welding experiment

voltage and wire feed speed. Therefore, a change of the gun position will change the welding current owing to the change of electrode extension [47].

![Schematic of GMAW process](image)

Figure 3.2: Schematic of GMAW process [15].

Generally speaking, according to the voltage and current levels, there are three metal transfer modes, namely short-circuit, globular and spray mode can be distinguished. These three modes are shown in figure 3.3. In the short-circuit mode, the drop size is smaller than the electrode diameter. The voltage and current of the short-circuit mode is relatively low. Due to its low heat input, this mode is suitable for thin plates [48]. The current of the globular mode is similar to that of the short-circuit mode, but the voltage is higher. The drop size is larger than the electrode diameter. Between the globular mode and the spray mode, there is a transition current, above which the spray mode occurs [49]. Because of the high current and voltage, the heat input is fairly high. Hence, spray mode is suitable for thick plates.
3.1.3. Welding setting

Welding experiments were performed with a Fronius™ RCU 5000 I welding machine (figure 3.4). The electrode was a Böhler UNION NiMoCr filler with a diameter of 1.2 mm, which is classified as an ER 100S-G wire according to AWS A5.26 [51], compatible with the composition of S700MC steel. The chemical composition of this filler material can be found in table 3.3. The shielding gas was a mixture of Ar (85%)-CO₂ (15%) with a flow rate of 15 l min⁻¹. The contact tip to workpiece distance was kept constant as 15 mm and the torch was perpendicular to the workpiece. Ceramic bricks were positioned underneath the centre line of the welding plate to preserve and avoid molten metal adhering to the backing plate [1, 32].

Figure 3.3: Three metal transfer modes of GMAW [50].

Figure 3.4: The welding power source and remote control module.
3.1. Welding experiment

Table 3.3: The chemical composition of the ER100s-G filler wire [52]

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Mo</th>
<th>Al</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt.%</td>
<td>0.12</td>
<td>0.6</td>
<td>2.1</td>
<td>1.5</td>
<td>0.5</td>
<td>0.04</td>
<td>0.2</td>
</tr>
</tbody>
</table>

3.1.4. Welding for 4 mm-thick plates
The dimension of the 4 mm-thick welding plates is 100 × 250 × 4 mm³ and these plates were milled with an angle of 30° in advance. Before welding, two plates were tack welded (without gap) to form a “V” groove with an angle of 60° in order to achieve full penetration. The welding setup was basically similar to that of the two-pass welding of 8 mm-thick plates except for the change of welding parameters. Welding for 4 mm-thick plates was carried out in single pass. The details of the welding parameter for single-pass welding can be found in table 3.4, which is in the short-circuit mode:

Table 3.4: The optimal welding parameters of S700MC steel with a thickness of 4 mm.

<table>
<thead>
<tr>
<th>Pass</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Travel speed (mm s⁻¹)</th>
<th>Wire feed rate (m min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.7</td>
<td>198</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

3.1.5. Welding for 8 mm-thick plates
The dimension of the 8 mm-thick welding plates is 100 × 250 × 8 mm³ and the plates were also milled with an angle of 30° in advance. Before welding, two plates were tack welded together to form a “V” groove with an angle of 60° and a constant gap of 0.5 mm (figure 3.5) in order to achieve full penetration.

Figure 3.5: Two 8 mm-thick plates tack welded with a gap of 0.5 mm, marked by the black arrow.

The welding condition was chosen based on previous experiments by Gao et al. [1] with some modifications. With the selected welding conditions, the first pass is within the short-circuit range and the second pass is within the range of spray transfer mode with a higher voltage and current. The details of the welding condition are shown in table 3.5.
Table 3.5: The optimal welding parameters of S700MC steel with a thickness of 8 mm.

<table>
<thead>
<tr>
<th>Pass</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Travel speed (mm s(^{-1}))</th>
<th>Wire feed rate (m min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.1</td>
<td>215</td>
<td>5</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>29.1</td>
<td>346</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>

The 8 mm-plates were divided into two groups: single-pass welding and two-passes welding. The single-pass welding group was specimen welded for one pass with UIT. Specimen from two-pass welding was exactly the same with that of single-pass welding specimen except for the additional second pass welding to fill the “V” groove. The details of welding with UIT will be discussed later in section 3.3.

3.2. Thermal analysis and modelling approach

3.2.1. Temperature measurement

In order to obtain the temperature cycle at different locations, five K-type thermocouples were spot welded in the middle of the plate on the rear surface at various distances from the weld centre line. The accuracy of the temperature measurement is ±1°C and the uncertainty of the thermocouple positions is approximately 0.25 mm. A Yokogawa™ DL series oscilloscope was used to collect the thermocouple voltage signal, which has already been converted into the temperature. The experimentally obtained time dependent temperature data was used to validate the thermal field model of a 8 mm-thick plates with a single-pass welding to determine the temperature of weld bead. Figure 3.6 shows the transient temperature on the rear surface of the 8 mm-thick plates during the single-pass welding at five points: 2.5 mm, 9.5 mm, 19.7 mm, 29.0 mm and 47.5 mm from the weld centre line. The sampling rate of the oscilloscope is 1 Hz. In figure 3.6, the nearest point (2.5 mm) reaches the peak temperature firstly, followed by the second point (9.5 mm), the third point (19.7 mm) and until the last point (47.5 mm). In addition, the peak temperature decreases with the increasing distance from the weld centre line.
3.2. Thermal analysis and modelling approach

3.2.2. Welding thermal field model

The transport phenomena are extremely complex in GMAW, containing heat flow in the electrode, weld pool, arc and workpiece, which is shown in figure 3.7. Many forces are acting on the weld pool, including drag force, electromagnetic force, buoyant force, plasma force and impact force [53–55]. Experimentally, it is of great difficulty to measure the temperature distribution within the weld pool and it is also quite difficult to model it numerically. To make it simple, all phenomena related to electrode and arc are reduced into one expression as an input volume heat flux [56, 57]. In addition, fluid flow inside the weld pool and heat redistribution are also included by the distribution of the heat flux.
The heat source generates a heat flux, which is transferred into the workpiece. When heat enters the workpiece, it is primarily distributed by heat convection according to Fourier’s law of isotropic heat conduction. At the boundaries of the workpiece, heat is lost by means of conduction, convection and radiation. Figure 3.8 shows the schematic of heat transfer during welding.

In order to use finite element method (FEM) to proceed computational simulation, an accurate simulation of heat source is required. One of the most commonly used heat source models is based on Goldak’s double ellipsoid heat source model [56]. The front half of the source model is the quadrant of one ellipsoid, and the rear half is the quadrant of another ellipsoid, which defines two heat fluxes in the front and rear section of the heat source, $q_1(x, y, z, t)$ and...
3.2. Thermal analysis and modelling approach

\[ q_2(x,y,z,t) = \frac{6\sqrt{3}f_2Q}{abc_2\pi\sqrt{\pi}} \exp\frac{-3x^2}{a^2} \exp\frac{-3y^2}{b^2} \exp\frac{-3(z+vt)^2}{c_z^2} \]  

(3.2)

In Equation 3.1 and 3.2, \( f_1 \) and \( f_2 \) are fractional factors of the heat deposited in the front and rear quadrants, where \( f_1 + f_2 = 2 \). \( Q \) is the heat input and \( v \) is the travel speed. \( a, b, c_1 \) and \( c_z \) are constants, which are shown in figure 3.9:

![Goldak's double ellipsoid heat source configuration](image)

Figure 3.9: Goldak’s double ellipsoid heat source configuration [56].

The distribution and magnitude of the heat source are calculated based on an almost linear relationship between the weld pool geometry and heat input, which is proposed by Wahab [59] and Wang [60]. The welding parameters such as voltage, current, travel speed can be measured experientially. Along with the efficiency of welding process, heat input can be determined.

Once the heat enters the workpiece, there are heat losses occurring with the backing plates, clamping system and the surroundings, in terms of heat convection, which can be defined as:

\[ q_c = h(T - T_0) \]  

(3.3)

where \( q_c \) is the heat flux due to convection, \( h \) is the heat transfer factor, \( T \) is the temperature at the surface of the workpiece and \( T_0 \) is room temperature. Heat loss due to radiation is expressed by the following equation:

\[ q_r = \varepsilon\sigma_b(T^4 - T_0^4) \]  

(3.4)
where \( q_r \) is the heat flux due to radiation, \( \varepsilon \) is the radiation emissivity and \( \sigma_B \) is the Stefan-Boltzmann constant. Based on the energy conservation law \([61]\), there is a heat balance between heat flux and the change of stored energy:

\[
\rho \dot{H} = Q - \nabla \cdot \mathbf{q}
\] (3.5)

where \( \rho \) is the density, \( \dot{H} \) is the changing rate of enthalpy, \( Q \) is the power per unit volume and \( \mathbf{q} \) is the heat flux vector. The changing rate of enthalpy is related to the changing rate of temperature as well as the heat capacity:

\[
\frac{dH}{dt} = c_p \frac{dT}{dt}
\] (3.6)

where \( H \) is the enthalpy, \( c_p \) is the heat capacity. According to Fourier’s law of isotropic heat conduction:

\[
\mathbf{q} = -k \nabla T
\] (3.7)

In the above equation, \( T \) is the temperature and \( k \) is the thermal conductivity, dependent on the chemical composition, microstructure, and temperature \([62]\). The combination of the above equations gives the classical equation of conservation of energy:

\[
\rho c_p \frac{\partial T}{\partial t} = Q + \nabla \cdot (k \nabla T)
\] (3.8)

The initial temperature of the workpiece is room temperature. The heat losses due to the clamping system, backing contact, heat convection and radiation are modelled as boundary conditions.

### 3.2.3. Modelling approach

The welding parameters (voltage, current and travel speed) are shown in table 3.5, which was applied for the 8 mm-thick plate with a single-pass welding. Based on Goldak’s equation, the transient three dimensional temperature distribution was numerically investigated by COMSOL Multiphysics®. \( f_1 \) and \( f_2 \) are set as 0.7 and 1.3, respectively. The heat efficiency is 0.75. From the experimental weld pool geometry, the heat source parameters \((a, b, c_1, c_2)\) were obtained, which are listed in table 3.6.

**Table 3.6: Experimental heat source parameters for Goldak’s model.**

<table>
<thead>
<tr>
<th>a (mm)</th>
<th>b (mm)</th>
<th>c_1 (mm)</th>
<th>c_2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>5.6</td>
<td>3.5</td>
<td>7</td>
</tr>
</tbody>
</table>

As discussed in section 3.2.2, there are heat losses owing to convection, conduction and radiation. The heat transfer coefficient is 30 W m\(^{-2}\) K\(^{-1}\), including convection, which is based on the prediction of heat transfer by Pazooki \([16]\). The initial temperature was assumed to be room temperature, which is 25 °C.
3.2. Thermal analysis and modelling approach

The dimension of the plate is $250 \times 200 \times 8$ mm$^3$ (two 8 mm-thick plates with tack weld). The plate was modelled as a 3D model with quadratic tetrahedron elements. The region close to the welding centre line is modelled with denser meshes, while the region close to the edge has a relative larger mesh size. As the welding is symmetrical, only one half of the cross-section was modelled to save calculation time. The 3D model with meshes is given in figure 3.10.

![Figure 3.10: Meshes of the 3D model.](image)

Other thermal properties of S700MC were also included in this model according to Gao’s [1] research, which is shown in figure 3.11. It took approximately 400 s to finish the calculation.

![Figure 3.11: Thermal and mechanical properties of S700MC as a function of the temperature [1].](image)
3.2.4. Results of the temperature measurement and validation of the thermal model

Figure 3.12 shows the transient temperatures on the rear surface of the plate at five points: 2.5, 9.5, 19.7, 29.0 and 47.5 mm from the weld centre line. At these five reference points, the transient temperatures during welding and cooling stage are shown. The dotted lines represent the calculated temperature, while the solid lines give the result of the experimental measurements of temperature by means of thermocouple. As can be seen in figure 3.12, the experimental measurements and the numerical simulations are in good agreement in terms of thermal cycles and peak temperatures. For the reference point at 47.5 mm, the experimental result is a little lower than the simulation results. This deviation maybe due to the fact when the point is far away from the weld centre line, boundary conditions are not appropriate enough.

![Figure 3.12: Experimental and calculated temperature on the rear surface of the plate as a function of time at several distances from the weld centre line.](image)

With this thermal model, the temperature of the weld bed after a certain period of time can be calculated. This will determine the treating temperature of UIT, which will be discussed further in section 3.3.2.
3.3. Ultrasonic impact treatment

3.3.1. UIT holder and setup

The UIT equipment used in this experiment is an Esonix UIT system [63, 64], manufactured by Applied Ultrasonics™. This system consists of a generator, a cooling system and a hand hold pinning tool (see figure 3.13). The self-weight of the pinning tool is 30 N and the ultrasonic frequency is 27 KHz. Four pins are aligned together in a row with a pin diameter of 3 mm, converting the ultrasonic energy into mechanical force during treatment.

![UIT equipment](image)

*Figure 3.13: The UIT generator, cooling system and hand hold pinning tool [63].*

In order to obtain different treating temperatures and treating angles as well as a uniform treatment along the weld toe, a special UIT tool holder is required. As can be seen in figure 3.14, the concept of the design of the UIT tool holder is that the UIT tool can move in x, y and z direction. In addition, the UIT tool is also able to change the angle relative to the z direction.
In this welding experiment, the welding torch stays still, instead, the workbench moves. By means of the thermal model (section 3.1.3), the temperature of the weld bead in terms of cooling time can be obtained. Assuming the travel speed of the workbench is \( v \) and the distance between the welding torch and the UIT tool is \( L \) (see Figure 3.15), the time interval between welding and UIT treatment is \( t \):

\[
t = \frac{L}{v}
\]

(3.9)

\( t \) is the interval between welding and UIT treatment, which is also the cooling time after welding. For example, the smallest distance between the welding torch and UIT pinning tool is 70 mm and the travel speed is 5 mm s\(^{-1}\). With the help of equation 3.9, the cooling time is supposed to be 14 seconds. According to the result of the model in section 3.2.3, the temperature when UIT begins is supposed to be around 653 °C. Similarly, if the distance is kept as 100 mm, then the cooling time is 20 seconds and the treating temperature is around 495 °C. So generally speaking, by changing \( L \), the treating temperature in turn can be changed, which is shown in table 3.7. In figure 3.15, the schematic of the welding torch and UIT tool is shown.
Table 3.7: Treating temperature with various distances between UIT and torch, based on simulation model.

<table>
<thead>
<tr>
<th>Distance between UIT and torch (mm)</th>
<th>Time interval (s)</th>
<th>Treating temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>14</td>
<td>approximately 653</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>approximately 495</td>
</tr>
<tr>
<td>N.A</td>
<td>N.A</td>
<td>room temperature</td>
</tr>
</tbody>
</table>

3.3.2. UIT with different temperatures and angles

UIT combines the effect of ultrasonic energy and mechanical treatment. In order to investigate the effect of inter-pass UIT, different treating temperatures were chosen. According to the cooling curve of S700MC steel (CCT diagram, figure 3.16), when the temperature is around 653°C, the treating phase is austenite; for region between 590°C and 475°C, the treating phase is in the region of ferrite and bainite. According to Gorka et al. [65], at around 500°C, recrystallisation of S700MC steel begins to happen. When the temperature drops to room temperature, the phase is also ferrite with bainite, but in a cold condition.
Figure 3.16: CCT diagram of S700MC steel\([65]\). 1 is in the austenite region, 2 is in the ferrite and bainite region (warm condition) and 3 is also in the bainite and ferrite region (room temperature).

The black line indicates the cooling curve of the weld bead.

Also the treating angles have an influence on UIT. The treating angle determines the resolved force. With an vertical angle relative to the weld toe, the normal force is maximum (figure 3.17) and therefore more compressive force is applied with more severe plastic deformation. Considering the diameter of the pins (3 mm), it is not possible to treat the weld toe with an angle of -30° parallel to the “V” groove. Therefore, the treatment with an angle of 30° was applied, which is shown in figure 3.18.
3.3. Ultrasonic impact treatment

UIT tool was mechanically mounted in another frame adjacent to the welding touch, which is shown in figure 3.19. With this frame, the distance between the UIT tool and the welding torch (UIT treating temperature) can be changed and the treating angle can also be changed. UIT was applied to both of the weld toes during the inter-pass welding with different treating parameters. As the UIT tool has only one transducer, only one of the weld toes was treated with the constantly high temperature, while the other one was treated with a relatively low temperature after the first weld toe was treated.
3. Experimental procedures

The experiment was divided into several groups. Ref 1 is the reference sample with only single-pass welding and ref 2 is another reference sample with two-pass welding. As for sample 1 to 12, they were treated with different treating temperatures and treating angles. The details of the UIT conditions are shown in table 3.8. Similarly, the welding and UIT experimental conditions for the 4 mm-thick plates (single-pass welding) are shown in table 3.9.
### 3.3. Ultrasonic impact treatment

#### Table 3.8: Welding with UIT experiment for 8 mm-thick plates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Torch to UIT distance (mm)</th>
<th>Treating temperature (°C)</th>
<th>Treating angle (°)</th>
<th>Welding pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref 1</td>
<td>N.A</td>
<td>N.A</td>
<td>N.A</td>
<td>1</td>
</tr>
<tr>
<td>Ref 2</td>
<td>N.A</td>
<td>N.A</td>
<td>N.A</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>approximately 653</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>approximately 653</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>approximately 653</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>approximately 653</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>approximately 495</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>approximately 495</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>approximately 495</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>approximately 495</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>N.A</td>
<td>Room temperature</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>N.A</td>
<td>Room temperature</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>N.A</td>
<td>Room temperature</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>N.A</td>
<td>Room temperature</td>
<td>30</td>
<td>2</td>
</tr>
</tbody>
</table>

#### Table 3.9: Welding with UIT experiment for 4 mm-thick plates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Torch to UIT distance (mm)</th>
<th>Treating temperature (°C)</th>
<th>Treating angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>N.A</td>
<td>N.A</td>
<td>N.A</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>660 (estimated)</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>N.A</td>
<td>Room temperature</td>
<td>90</td>
</tr>
</tbody>
</table>
3.4. Digital image correlation and welding distortion

Digital image correlation is a relatively new method to measure the full-field displacement contour of an object. In order to measure the out-of-plane displacement, a 3D-DIC with two cameras is required. The 3D-DIC is based on the principle and algorithm of stereovision. In the experiment, a Limess Q-400 3D-DIC system was used and the result was analysed by the Insra 4D software. Before the measurement, two cameras needed to be calibrated with a special calibration target with black and white grids on it (figure 3.20) [66]. The calibration defined the initial origin, x axis, y axis and residuum. The residuum is the average uncertainty of the found markers in the unit of pixels, determining the accuracy of the measurement. Typically the smaller the residuum is, the more accurate the measurement is.

![Calibration target of 3D-DIC made of aluminium](image)

*Figure 3.20: Calibration target of 3D-DIC made of aluminium [66]. The blue arrows indicate the axes and origin.*

Figure 3.21a demonstrates the setup of the 3D-DIC experiments. Before measurement, the welding plate were painted with a random white and black speckle pattern (figure 3.21b). This speckle pattern was recognised by the system and the system gave the correlation of the displacement and the 3D-coordinate of each grid point. Before measurements, an arbitrary flat plate with the same thickness was measured and compared with plates after welding and UIT. The correlation parameters setting was based on experiments of Popovich [67] and are shown in table 3.10.
3.4. Digital image correlation and welding distortion

Figure 3.21: (a) Setup of 3D-DIC. (b) Welding plates with speckle patterns.

Table 3.10: Instra 4D correlation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Setting</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facet size</td>
<td>25</td>
<td>pixels</td>
</tr>
<tr>
<td>Image levels</td>
<td>two levels</td>
<td>-</td>
</tr>
<tr>
<td>Outlier tolerance</td>
<td>low</td>
<td>-</td>
</tr>
<tr>
<td>Maximum permissible values</td>
<td>0.5</td>
<td>pixels</td>
</tr>
<tr>
<td>Residuum</td>
<td>20</td>
<td>grey values</td>
</tr>
<tr>
<td>3D residuum</td>
<td>10</td>
<td>pixels</td>
</tr>
<tr>
<td>Grid spacing</td>
<td>20</td>
<td>pixels</td>
</tr>
</tbody>
</table>
3.5. **Contour mapping method for residual stresses**

Contour mapping is a method to measure the uni-axial residual stresses based on the Bueckner’s superposition principle [25]. As only a few institutions have the access to the neutron diffraction or the high-energy X-ray diffraction to measure through-thickness residual stresses, therefore, contour mapping method becomes a complement, which is proved to have a relatively high accuracy.

The welding plates were first cut with wire EDM, which produced very limited extra stresses. After cutting, due to residual stresses relaxation, convex and concave shapes formed. Owing to the limitation of equipment, the surface profile was measured by either a laser scanner or a confocal microscope. The laser scanner was an optoNCDT 1402-5 triangulating laser sensor. As can be seen in figure 3.22a, the laser scanner was scanning the whole surface of the cross-section controlled by a motor made by Galil Motion Control, which generated the raster pulse. The vertical displacement was converted into a voltage signal, collected by an oscilloscope. Figure 3.22b shows the working mechanism of a laser scanner. The surface profile was also measured by a Keyence VHX-5000 confocal microscope, which is based on the mechanism of 3D composition depth analysis.

![Image](a.png)  
![Image](b.png)

*Figure 3.22: (a) Setup of laser scanner. (b) Working mechanism of triangulating laser scanner [68].*

After the measurement of the surface profile, the data underwent a sequence of data processing, including noise reduction, smoothing of data, interpolating and averaging. Finally, the data was imported into FEM to calculate the original stresses distribution.

3.6. **Microstructure and micro-hardness investigation**

The microstructures of the weld metal, HAZ, UIT treated zone were studied at a cross-section perpendicular to the weld and in the middle of the plates. The cross-section experienced several processes including mounting, grinding, polishing before it was finally etched with the Nital 5% solution for 4 seconds. Then, the microstructures were observed with the help of a
Keyence VHX-5000 confocal microscope, which is shown in figure 3.23.

The effect of UIT was also quantified by the micro-hardness test. Vickers micro-hardness tests were performed with a Struers DuraScan70 micro-hardness testing machine (figure 3.24) with a square pyramidal shaped diamond indenter. This machine can apply different loads to the cross-section and according to ASTM C1327 [70], the space between the centres of two indentations should be at least four times of the diagonal length in order to avoid the effect of plastic deformation.
3.7. Charpy V-notch impact test

Charpy V-notch impact tests were carried out to investigate the mechanical properties of the two-pass as-welded plates, plates with inter-pass UIT at room temperature and plates with UIT at approximately 653°C. As the thickness of the plates was 8 mm, therefore, the plates were machined into sub-size specimens, which is described in section 2.4. The position of the notch were determined with the help of microscopy. For example, the microscopy of a single-pass plate with UIT at approximately 653°C was studied. The area affected by UIT is marked by the red lines in figure 3.25a. Since the boundary has been determined, the closest point near the boundary of UIT at the HAZ after the second welding was also determined, which is shown as the red cross-point in figure 3.25b. The notches in other samples were also determined in the same manner.

![Figure 3.25: (a) The microscopy of a single-pass plate with UIT treated on the right side and the red line indicates the UIT treated region. (b) The position of the V notch of a two-pass welding plate with inter-pass UIT, marked with a red cross-point and the position is x = 4.05 mm, y = 5.20 mm, from the weld centre line at the bottom of the plate.](image)

The tests were carried out at room temperature, -20°C and with a decrement of -10°C until -110°C. Three to five samples were tested at each chosen temperature in order to discriminate the system error. The tests were carried out according to ASTM E23.

3.8. Summary

In this chapter, Based on the temperature measurements, the thermal model was validated. After that, the design of UIT tool holder as well as welding experiments with UIT were described. Finally, methods to characterise welding distortion, residual stresses, microstructures, micro-hardness and fracture resistance were introduced, respectively.
Results

In chapter 3, the experimental procedures and different characterisation methods were described. The experiments were conducted for 4 mm-thick plates and 8 mm-thick plates, respectively. The results of welding distortion, residual stresses, microstructures, micro-hardness and Chapry V-notch impact tests will be presented in this chapter.

As stated earlier, DIC was used to measure the out-of-plane distortion after welding and UIT for both 4 mm-thick and 8 mm-thick plates. Contour mapping method was applied to measure the longitudinal residual stress for 8 mm-thick plates. Microstructures and micro-hardness were first conducted for 8 mm-thick plates with single-pass welding and UIT. Then, plates with two-pass welding and inter-pass UIT were also investigated. Finally, sub-size Chapry V-notch impact tests were performed at various temperatures for two-pass plates with inter-pass UIT.

4.1. Distortion measurement

4.1.1. Measurement of initial plates

The initial unwelded plates are set as the reference plates, therefore, their deformation plays a very important role. Although for many plates used in the experiment, the initial out-of-plane displacement is nearly zero, it is still worth measuring the initial plates to investigate the distortions of the reference plates. Figure 4.1 shows the initial out-of-plane displacement of the reference plates. The initial distortion is within the range of -0.3 to 0.2 mm, which is negligible compared to the relatively large distortion due to welding. So it is quite safe to assume the original plates are flat.
4. Results

Figure 4.1: (a) The distortion of the original 4 mm-reference plate. (b) The distortion of the original 8 mm-reference plate. Both the distortions are between -0.3 mm and 0.2 mm.
4.1.2. Measurement of 4 mm-thick plates

The 4 mm-thick plates were welded for single pass to investigate the effect of UIT treating temperature. These three sets of experiments were 4 mm-thick as welded plate, 4 mm-thick plates treated at room temperature and 4 mm-thick plate treated at about 660 °C. As can be seen in figure 4.2a and 4.2b, the out-of-plane distortion of 4 mm-thick as-welded plates is between 0 and 7.8 mm and that of 4 mm-thick plates with UIT at room temperature is within the range of 0 to 7.0 mm, and the area with high distortion becomes smaller. As expected, the out-of-plane distortion of 4 mm-thick plate with UIT at hot condition is alleviated significantly. As can be seen in figure 4.2c, the maximum distortion is only 4.5 mm, which only shows up at the edge of plate along the y direction and the distortion gradient is also decreased substantially. The details of the welding distortion measurements can be found in table 4.1.
4. Results

Figure 4.2: Distortion of (a) as-welded plates, (b) UIT treated at room temperature and (c) UIT treated at high temperature.

Table 4.1: The maximum out-of-plane distortion of 4 mm-thick welded and treated plates.

<table>
<thead>
<tr>
<th>Condition</th>
<th>maximum distortion (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As welded</td>
<td>7.8</td>
</tr>
<tr>
<td>UIT at room temperature</td>
<td>7.0</td>
</tr>
<tr>
<td>UIT at about 660 °C</td>
<td>4.5</td>
</tr>
</tbody>
</table>

4.1.3. Measurement of 8 mm-thick plates

The 8 mm-thick plates were also measured with DIC to investigate the welding distortion. As can be seen in figure 4.3, the distortions of a 8 mm-thick as-welded plates and plates with inter-pass UIT are both very small, within the range of 0 to 0.5 mm. The presence of the scattered light blue areas in 4.3b is due to the inconsistency of the speckle pattern. The light reflection also interferes the results. It seems that 8 mm-thick plates are too stiff and are not very easy to deform by welding. So it is very difficult to distinguish the benefit of inter-pass UIT in terms of distortion when there are no major distortions.
4.1. Distortion measurement

Figure 4.3: Distortion of (a) as-welded plates, (b) plate with inter-pass UIT. Both plates have very small distortion.
4.2. Microstructures

4.2.1. Microstructures of as-welded S700MC steel plates

A cross-section of the two-pass weld without UIT is shown in figure 4.4. Different regions can be well recognised within the cross-section of the plate, namely fusion zone, heat affected zone (coarse-grain affected zone, fine-grain heat affected zone and inter-critical heat affected zone) and base metal.

![Figure 4.4: Cross-section of a two-pass welding without UIT.](image)

The fusion zone is the area where the base metal melts and mixes with the filler material. It primarily consists of acicular ferrite and a small amount of martensite (figure 4.5a). The coarse-grained affected zone (CGHAZ) is the zone close to the fusion boundary, where grain growth happens, consisting of ferrite and Widmanstätten ferrite. Also, traces of large prior austenite grains could be found (figure 4.5b). The fine-grained heat affected zone (FGHAZ) is the zone where grain growth is limited and nucleation happens. It consists of equiaxed fine grains (figure 4.5c). The inter-critical heat affected zone (ICHAZ) is the zone where the material is subjected to a peak temperature between the austenisation temperature and the eutectoid temperature, where ferrite and bainite form (figure 4.5d).
4.2. Microstructures

Figure 4.5: Microstructures of (a) fusion zone consisting of acicular ferrite, (b) CGHAZ consisting of acicular ferrite, Widmanstätten ferrite and trace of prior austenite grains, (c) FGHAZ consisting of equiaxed grains and (d) ICHAZ consisting of ferrite.

4.2.2. Microstructures of single-pass welding with UIT

Figure 4.6 gives the geometry of a single-pass weld with UIT at about 653°C on the right side and UIT at room temperature on the left side (vertical treatment). As expected, the indentation of UIT at a higher temperature is much deeper than that at room temperature. The red line indicates the area treated with UIT after welding.
Figure 4.6: Weld geometry after vertical UIT at about 653°C (right side) and room temperature (left side). The red line indicates the area treated by UIT.

Figure 4.7 shows the weld geometry after UIT at 30° at around 653 °C and room temperature. Again, the indentation of UIT at higher temperature is deeper. Compared with figure 4.6, when UIT is applied at 30°, HAZ began to be affected by UIT.

In order to investigate the effect of UIT on microstructural changes, the cross-section of a single-pass weld with UIT was investigated by the microscopy. After UIT, the near-surface layer was heavily deformed and other parts also show microstructural changes, such as grain refinement. Figure 4.8 shows the chosen area to study the effect of UIT.
Figure 4.8: (a) Scheme of microscopy of UIT treated zone from the cross-section. (b) Microstructures of the UIT treated zone, marked with red line. Region 1-4 defines the different regions affected by UIT.

Figure 4.9a shows the microstructure of the white layer (region 1), which is the plastic deformation zone accompanied with local heating and removal of material and not apt to etching [1, 2, 8]. Figure 4.9b shows the microstructures of the near-surface layer from single-pass welding with UIT. It is evident that the near-surface is the “pancake” zone, where the grains are elongated along the transverse direction (region 2). With increasing depth from the surface, the “pancake” zone began to disappear gradually. Then, the plastic zone is visible, where the grains are refined (region 3) compared with the undeformed zone (figure 4.9c and figure 4.9d ). With further increasing depth form the top surface in normal direction, the effect of plastic deformation due to UIT became less apparent (region 4). However, it is very difficult to distinguish the boundary of the UIT affected zone and the non-UIT affected zone based on the microscopy.
4.2.3. Microstructures of two-pass welding with inter-pass UIT

After UIT, a second weld was applied so that the welding groove was completely filled. After the second weld, the UIT treated zone was remelted and only a small part may survive in the HAZ, where micro-hardness tests were carried out.

Figure 4.9: Microstructures of the (a) white layer, (b) "pancake" zone, (c) plastic deformation zone with refined acicular ferrite and (d) undeformed zone with bigger grains of acicular ferrite.
4.3. Micro-hardness

4.3.1. Hardness of single-pass welding without UIT

In order to get a first impression on the hardness of the base metal, fusion zone and HAZ, micro-hardness measurements were first performed transverse to the weld centre line of a single-pass welding plates over an area of 5 × 15 mm². The increment along the vertical direction is 0.5 mm and along the horizontal direction is 1 mm. The measurement was performed with a load of 0.5 kg to investigate the hardness distribution within the as-welded specimen. The indentions were analysed with ecos Workflow software. The hardness distribution within the as-welded specimen is shown in figure 4.10.

![Figure 4.10: Micro-hardness distribution of the single-pass welding without UIT along the transverse plane of the weld (8 mm thick).](image)

In the fusion zone, the microstructures primarily consist of acicular ferrite, which has an overall hardness between 280 to 300 $H_{V0.5kgf}$. Acicular ferrite has the potential of combining high strength and high toughness [71]. The hardness variation is due to the heterogeneity of the acicular ferrite grain size and the presence of martensite. In the weld metal region very close to the fusion boundary, the hardness rises to between 300 and 320 $H_{V0.5kgf}$, which is due to the fast cooling (the cooling rate is approximately 40 °C s⁻¹). The hardness drops to between 220 and 240 $H_{V0.5kgf}$ in the coarse-grain heat affected zone. Then, the hardness rises again to the range of 240 to 260 $H_{V0.5kgf}$ in the fine-grain heat affected zone. Finally, the hardness of the base metal (S700MC) is within the range of 260 to 280 $H_{V0.5kgf}$. 
4.3.2. Hardness of single-pass welding with UIT

Since the hardness of the as-welded plates has been investigated, it is also worth measuring the hardness of single-pass welding plates with UIT. Samples are plates with single-pass welding and UIT vertically at room temperature, vertically at approximately 653°C and at room temperature with a 30° angle. Micro-hardness measurements were also performed transverse to the weld centre line over an area of 7 × 12 mm². The increment along the vertical direction is 0.5 mm and along the horizontal direction is 1 mm. The measurements were also performed with a load of 0.5 kg. The hardness distribution within a sample with UIT is shown in figure 4.11.

As can be seen in figure 4.11a, after UIT at room temperature vertically, the area with a hardness between 300 and 320 $H_{V_{0.05kgf}}$ becomes large. The area beneath UIT has a higher hardness, between 320 and 360 $H_{V_{0.05kgf}}$.

When the treating temperature increases to about 653°C, the UIT indentation becomes deeper and the UIT affected zone is wider, which is shown in both figure 4.11b. When the load is 0.5 kg, the mean diagonal length of the indentation is about 60 μm. In order to improve the accuracy of the hardness measurement, the measurement started at the position four times of the diagonal length (240 μm) from the top surface. In this 240 μm range, hardness measurement with a load of 0.05 kg was applied. The maximum hardness is around 360 $H_{V_{0.05kgf}}$ at approximately 653 °C, while that of room temperature is around 380 $H_{V_{0.05kgf}}$.

When the treating angle changes to 30° just as figure 3.18 shows, resolved force in the normal direction decreases while that in the transverse direction increases. As can be seen in figure 4.11c, UIT treated at 30° begins to affect HAZ, while UIT in vertical direction mainly affects the fusion zone. The peak hardness after UIT with a 30° angle, as expected, is lower than that in the vertical direction, therefore, the hardness gradient in HAZ decreases. It is also apparent that UIT at 30° results in a lower peak hardness compared with that of UIT vertically.
4.3. Micro-hardness

Figure 4.11: Micro-hardness distribution of (a) UIT vertically at room temperature, (b) UIT vertically at approximately 653°C, and (c) UIT at approximately 653°C and room temperature with a 30° angle, along the transverse plane of the weld.
4.3.3. Hardness of two-pass welding without UIT

Hardness measurement of two-pass as-welded plate was performed transverse to the weld centre line of a two-pass welding plates over an area of $7 \times 16 \text{ mm}^2$. The increment along the vertical direction is 0.5 mm and along the horizontal direction is 1 mm. The measurement was performed with a load of 0.5 kg. Figure 4.12 shows the hardness map of the two-pass weld without UIT.

![Figure 4.12: Micro-hardness distribution within two-pass welding without UIT along the transverse plane.](image)

Due to the remelting of second-pass welding, the hardness of the fusion zone is only around $240 \text{ to } 280 \, H_{0.5\text{kgf}}$, which is lower than that of the single-pass without UIT (figure 4.10). With decreasing $y$, the effect of remelting becomes less and the hardness of the fusion zone increases a little bit. Compared with figure 4.10, the HAZ of two-pass welding is wider than that of single-pass welding due to the higher heat input. Besides the above characteristics, the hardness distribution inside the two-pass welding, in general, is similar to the single-pass welding.

4.3.4. Hardness of two-pass welding with inter-pass UIT

Hardness measurement of two-pass welding with inter-pass UIT used the same setup and parameters described in section 4.3.3. Figure 4.13 shows the hardness map of the two-pass welding with inter-pass UIT.
4.3. Micro-hardness

(a) Two-pass welding with UIT at room temperature, vertically

(b) Two-pass welding with UIT at approximately 653°C, vertically

(c) Two-pass welding UIT at room temperature and 653°C, 30°

Figure 4.13: Micro-hardness distribution of the two-pass welding with inter-pass UIT (a) vertically at room temperature, (b) vertically at approximately 653°C and (c) with a 30° angle at approximately 653°C and room temperature, along the transverse plane.
Figure 4.13 illustrate the hardness gradient within two-pass welding with inter-pass UIT vertically at room temperature, vertically at approximately 653 °C and with a 30° angle at about 653 °C and room temperature, respectively. Unfortunately, after the second weld, a large part of the first pass, including the white layer, “pancake” zone and plastic-deformation zone was remelted. There is barely a difference between the three mentioned conditions. As can be seen in figure 4.13b, point 1 and point 2 have a hardness difference of 30 H\textsubscript{V,0.5kgf}. In order to investigate the hardness difference, microscopy around these two points were applied, which is shown in figure 4.14. Point 2 has a finer grain size than point 1, resulting in a higher hardness.

![Microscopy Image](image1)

**Figure 4.14:** The microscopy of (a) point 1 and (b) point 2 shown in 4.13 (b).
4.4. Charpy V-notch impact test results

This part is removed due to confidentiality.
4.5. Contour mapping results

4.5.1. Wire EDM results

The first problem of the contour mapping method is the wire EDM. As mentioned in the previous chapter, in order to achieve a precision surfaces with a low roughness, the skim cut was applied to the specimens. The specimens were first cut with a speed of 6 mm hr⁻¹, followed by a second cut with a speed of 1 mm hr⁻¹. Unfortunately, after EDM, the surface was very smooth that there were barely any contractions or expansions. The possible explanation is that the speed of EDM is too slow that even if there are visible deformations, they are recut by the later machining.

4.5.2. Surface contour results

Although the EDM results are not successful, it is still worth investigating the feasibility of surface contour measurements by laser scanner and confocal microscope. Figure 4.15 shows the surface contour results of a hole on a flat surface measured by the laser scanner and the confocal microscope. Comparing figure 4.15a and figure 4.15b, the contour results measured by the laser scanner contains a lot of fluctuations, which interferes the final result. However, the surface contour measured by the confocal microscope is relatively smooth and can reproduce the profile better than the laser scanner.
4.6. Summary

The DIC results of 4 mm-thick plates show that UIT can reduce the distortion at room temperature and the reduction is even greater when the treating temperature is higher. Unfortunately, distortion of 8 mm-thick plates is too small even for the as-welded condition, therefore, it is not appropriate to draw a conclusion of the effect of inter-pass UIT from the perspective of distortion. After UIT, severe plastic deformation results in white layer, "pancake" zone, grain refinement. Along with the hardness measurement, the hardness of top surface is increased. At higher treating temperatures, the UIT indention is deeper and with an tilted treatment, the HAZ is affected. However, after the second weld, neither does the microscopy nor hardness show any improvement due to inter-pass UIT. As for the Charpy V-notch impact tests, both the USE and LSE of specimens with no inter-pass UIT, inter-pass UIT at room temperature and at about $653^\circ C$ shows very small difference. Nevertheless, the DBTT of specimens with inter-pass UIT decreases more than -10°C. Inter-pass UIT at about $653^\circ C$ also decreases the DBTT slightly compared to inter-pass UIT at room temperature.
Discussion

From the experiments, the results of welding distortions of 4 mm-thick and 8 mm-thick plates with UIT have been obtained. Microscopy, micro-hardness distribution and fracture resistance results of 8 mm-thick plates have also been acquired. In this section, the results form the previous chapter will be discussed.

DIC results show that the 4 mm-thick as-welded plate has the largest distortion. With UIT at room temperature, the maximum distortion decreases 0.8 mm and the area with high distortion becomes smaller. Furthermore, when the treating temperature is approximately $660^\circ C$, the maximum distortion decreases to 4.5 mm and the area with high distortion further reduces. According to [1], after UIT, the longitudinal stress is redistributed. The tensile stress close to the weld root and weld toes is reduced and the high-stress area is also reduced. When the workpiece is treated in a warm condition, additional compressive stress is introduced as the materials are much softer. The clamping system also has an effect on the welding distortion. In the experiments, the plates were not released from the clamping system until the plates cooled down to room temperature.

The 8 mm-thick plates were first welded with single pass and UIT at different temperatures. Due to plastic deformation induced by UIT, white layer and ultrafine grains form. With an increasing distance from the top surface, the ultrafine grains gradually change to a pancake structure at about 40 $\mu$m below the top surface. The pancake structure further changes to fine grains at approximately 110 $\mu$m below the top surface. When the distance is around 1.5 mm, the structure is acicular ferrite, unaffected by UIT. When the specimen is treated at about $653^\circ C$, the indentation is much deeper than that treated at room temperature. As stated earlier, the material are much softer in a warm condition. According to Davis et al.
yield strength of a steel decreases with the increasing temperature, which makes the steel softer and thus easy to deform. The micro-hardness results show that UIT increases the micro-hardness of the top surface. The increasing hardness indicates that UIT exerts a severe plastic deformation, increasing the dislocation density and causing work hardening [74]. In addition, UIT results in grain refinement (figure 4.9 (b)), causing grain boundary strengthening [37, 74–76]. However, the peak hardness with UIT at room temperature is higher than that of UIT at around 653°C. The reason is that, on one hand, at room temperature, the deformation is inhomogeneous. While at a higher temperature, more homogenous distribution of dislocations occurs. More slip systems are also available at a higher temperature and dislocations can move more easily [41, 74, 77], which relieves the effect of work hardening, resulting in a lower peak hardness; on the other hand, at about 653°C, the treating phase is austenite (FCC) and at room temperature, the treating phase is ferrite (BCC) with bainite (see figure 3.16). It is widely accepted [78–80] that austenite with FCC has a lower stacking fault energy, which increases the difficulty of cross-slip. Therefore, during plastic deformation, the ability of the materila to change its shape by slipping decreases, resulting in the occurrence of twinning [77]. Furthermore, at about 653°C, the recovery and recrystallisation process initiates and new defect-free crystals form, which soften the materials [65]. According to Cizek [81], due to plastic deformation of austenite, high dislocation density is created. The increasing free energy of austenite reduces the critical energy for ferrite nucleation. The severe plastic deformation of parent austenite enhances the formation of polygonal ferrite (PF) and quasi-polygonal ferrite (QF). It has been widely accepted [82–84] that the enhanced PF or QF formation decreases the hardenability of the steel, making it softer.

The DIC results of the 8 mm-thick plates with inter-pass UIT indicates that the distortion is very small. There is no remarkable change between 8 mm-thick as-welded plates and 8 mm-thick plates with inter-pass UIT in terms of distortion. The reason is that the 8 mm-thick plates are too stiff and the deformation is difficult to occur. After the second pass, a large part of the UIT affected zone is melted. Neither does the microscopy nor the micro-hardness shows any improvement by inter-pass UIT.

In order to investigate the residual stresses distribution inside the 8 mm-thick plates with inter-pass UIT, contour mapping method was applied. Unfortunately, the results are not successful. The unsuccessful measurements are due to the wire EDM process and surface profile measurements. First of all, after wire EDM, the surface of the cross-section showed no effective contraction and expansion, which means the residual stresses in the weld has already been released. A set of optimised EDM parameters is required to proceed the measurement. Secondly, the surface profile measurements contain large scatters when the laser scanner was applied. In order to analyse the error of the laser scanner, a 5 mm-long line on a surface was scanned by the lase scanner with an increment of 1 mm, 0.5 mm, 0.2 and 0.1 mm, respectively. As can be seen in figure 5.1, the displacements of the same point with different scanning increments coincide very well. For the measurement with an increment of 1 mm, the
fluctuation between two points are relatively large. However, the measurements with smaller increments provide more specific details between two points, showing the same trend.

The line measurements by the laser scanner shows that the accuracy of the laser scanner is relatively high. According to the manual, the best resolution of the laser scanner is 0.6 µm and the spot diameter is between 110 and 650 µm, dependent on the measuring range. So the possible explanation for the large scatters is that many details of the surface profile are missed due to the large spot diameter. The confocal microscope can reproduce the surface profile very well. According to [87], the accuracy can reach 1 µm at a magnification of 1000x. However, the error occurs during the process of stitching. When a high magnification is applied, only a small area can be scanned. Therefore, in order to measure the whole surface, several pictures are stitched together. Overlapping occurs at the edge of two adjacent pictures, causing measurement errors. Another restriction of the confocal microscope is the scanning area. Even with the stitching process, the maximum scanning area is 20 × 20 mm² at a magnification of 1000x, which is not suitable for large cross-sections.

As the distortion, microscopy and micro-hardness results show no remarkable change due to inter-pass UIT, sub-size Charpy V-notch tests were applied. The Charpy test results show that ductile-to-brittle transition temperature (DBTT) is lowered with inter-pass UIT at room temperature and further lowered with inter-pass UIT at a higher temperature. The introduction of compressive stress via UIT, furthermore, hinders the crack initiation, increasing the energy absorption before fracture in Charpy V-notch impact tests. Besides,
the compressive stress is beneficial to lower the DBTT. Nevertheless, the data of specimen with inter-pass UIT at about 653°C contains a lot of scatters. The large scatters increases the uncertainty of the test results. Therefore, microscopy is required to study the effect of positioning of the V notch on the absorbed energy.
Conclusion and recommendation

The DIC results of 4 mm-thick plates show that UIT reduces the distortion at room temperature and the reduction is even greater when treating temperature is higher. Unfortunately, distortion of 8 mm-thick plates is too small even for as welded condition, therefore, it is not appropriate to draw a conclusion of the effect of inter-pass UIT from the perspective of distortion. After UIT, severe plastic deformation results in microstructure modifications. The hardness of the top surface is increased. At a higher treating temperature, the UIT indention is deeper. When the pinning tool is tilted, the HAZ begins to be affected by UIT. However, after the second pass, welding distortion, microscopy and micro-hardness do not show any improvement by inter-pass UIT. The Charpy V-notch tests show that the DBTT is lowered with inter-pass UIT at room temperature and further lowered with inter-pass UIT at a higher temperature.

In order to further investigate the effect of inter-pass UIT, the contour mapping method for residual stresses measurement needs to be modified. An optimal set of EDM parameters should be determined and a coordinate measuring machine (CMM) is preferred to measure the surface profile. The residual stresses can also be measured by high energy XRD or the neutron diffraction. In addition, transmission electron microscopy (TEM) could be applied to observe twinning forming during UIT at a high temperature. For Charpy V-notch impact tests, thicker plates with inter-pass UIT are recommended so that full-size Charpy V-notch tests can be performed. The location of the V-notch also needs to be repositioned to avoid misorientation and scattering of the results.
Bibliography


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<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>CCT</td>
<td>Continuous cooling transformation</td>
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<tr>
<td>CGHAZ</td>
<td>Coarse-grained heat affected zone</td>
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<tr>
<td>CHD</td>
<td>Centre hole drilling</td>
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<tr>
<td>CMM</td>
<td>Coordinate measuring machine</td>
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<tr>
<td>DBTT</td>
<td>Ductile-to-brittle transition temperature</td>
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<td>DIC</td>
<td>Digital image correlation</td>
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<tr>
<td>EDM</td>
<td>Electrical discharge machining</td>
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<td>FEM</td>
<td>Finite element method</td>
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<td>FGHAZ</td>
<td>Fine-grained heat affected zone</td>
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<tr>
<td>GMAW</td>
<td>Gas metal arc welding</td>
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<tr>
<td>HAZ</td>
<td>Heat affected zone</td>
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<tr>
<td>ICHAZ</td>
<td>Inter-critical heat affected zone</td>
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<td>LSE</td>
<td>Lower shelf energy</td>
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<tr>
<td>PF</td>
<td>Polygonal ferrite</td>
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<td>QF</td>
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<tr>
<td>TEM</td>
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<td>UIT</td>
<td>Ultrasonic impact treatment</td>
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<tr>
<td>USE</td>
<td>Upper shelf energy</td>
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<td>X-ray diffraction</td>
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