Cracks Forming and Propagation Mechanism for the Q345 Steel during Cooling

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Abstract. Cracks always occur for the Q345 steel during cooling, which usually lead to Welding failure. Through investigation of the cracks forming position and propagation path, its forming and propagation mechanism for the melted Q345 steel during cooling was studied in detail by using of SEM, EBSD and Nano Indenter equipment in this paper. SEM observation results imply that cracks mainly initiated at martensite phase region close to basal material. Moreover, it also can be observed that the cracks always propagated along the martensite lath or packets boundaries, but not the original prior austenite grain boundaries. The hardness differences between cracks adjacent positions and matrix is about 2.48 GPa, which is larger than that of melted region and matensite (0.70GPa). In addition, EBSD results show that the average prior austenite grains boundaries angles (30- 50°) are always smaller than that of martensite lath and packet boundaries (>50°). Combining investigation of the cracks forming position, propagation path and microstructure misorientation, it proves that the occurrence of the cracks at junction of martensite phase region close to basal material is related with larger hardness difference or larger residual stress between martensite and ferrite, while cracks propagation path is controlled by the boundaries angles or local misorientation. The cracks incline to propagate along or deflect to large martensite lath and packets boundaries.

1 Introduction

Q345 has been widely used in the production of storage tank and buildings\textsuperscript{[1-3]}. However, it is very popular for the crack occurrence during welding because the martensite is prone to form at the hot affected zone, which will waste lots of material for manufacture of large products. Up to now cracks initiation and propagation mechanisms have been widely investigated for the Q345 welded joint fatigue cracks \textsuperscript{[4-5]}. Moreover, computer simulation methods were also attempted to investigated central crack closing behavior during ultra-heavy plate rolling\textsuperscript{[6]}. Some studies turn out that welding residual stress has great effect on the fatigue crack propagation rate of the weld metal\textsuperscript{[1]}. Igwemezie\textsuperscript{[7]} points out that crack deviation, crack branching and wedging action of metal crumbs retarded the crack growth by reducing the effective stress or driving force at the local crack tips. It was reported that the fatigue cracks growth resistance of the steel having a distributed pearlite structure was more than that of a networked pearlite structure \textsuperscript{[8]}. In a conclusion, the microstructure also has great effect on the cracks propagation growth rate and path.
That the relationship between microstructure and mechanical properties has been considerably studied [9-11]. Lots of reports prove that the inclusions can be the fatigue cracks source and the cracks are prone to initiate at the inclusions [12-13]. Meanwhile, crack behaviors for dual phase material also have been studied [12-16]. For the micro thickness laminate structure, the cracks always initiated at the ferrite with lower hardness and the phase boundary retard the crack growth rate. However, previous studies mainly focused on the stress concentration and fine microstructures on the fatigue cracks growth rate and cracks propagation path, there is little reports on cracks forming sensitivity for the large size multi-phase microstructure. However, it is important for the design of welding processing. In this paper, the cracks forming and propagation mechanism during continuous cooling was investigated in detail for the large size multi-phase microstructure.

2 Materials and experimental details

The material investigated in this experiment is Q345 plate (C 0.17, Si 0.30, Mn 1.27, P 0.018, S 0.0044, Cu 0.061, Ti 0.005, Al 0.044 wt.%) on which a small area was heated to melt and air cooled to room temperature used to obtain large size multi-phase without dispersed or laminated microstructure. The microstructure at melt location was sorbite or bainite after air cooling, while the microstructure at the unmetled position were martensite, ferrite and pearlite. In order to study the cracks forming and propagation mechanism for large size multi-phase microstructure, specimens of length 10mm and width 10mm with cracks were cut from the melted plate. After ground, polished and corroded with 4% Nital, the samples were observed by Quanta 650 SEM equipment. The accelerated voltage was 20KV and the working distance was 16mm. Cracks initiation position and propagation path were analyzed through concluding the microstructure around cracks. The microstructure orientation and boundary angles for the positions adjacent to the cracks were measured by using of EBSD used to analyze cracks propagation mechanism. The samples with cracks were ground and electro polished with 6% perchloric acid alcohol and 75mA constant current. The EBSD measurement was conducted with conditions of accelerated voltage 20KV, step size 200nm and measured area 60μm×60μm. In addition, EDS is used to ascertain the compositions of the inclusions so as to discuss the influence of the inclusions on the cracks propagation.

Nowadays, Nano indenter measurement has been widely used to investigate materials properties [17-20]. The advantage of nanoindentation technology over conventional methods is that it can provide micro mechanical properties of the material accurately. Former researchers have studied the hydrogen effect on the fatigue crack growth in austenitic stainless steel investigated based on nanohardness distribution [21]. In this paper, the nanoindentation tests were performed to measure the hardness for the different positions adjacent to the cracks, melted position and base metal by using of Agilent G200 equipment with displacement into surface 1500nm and strain rate 0.05s⁻¹. The Berkovich diamond tip with an effective tip radius is 20nm. The measurement location accuracy was calibrated before the nanoindentation test in order to make sure the exact measured position is the set position. In addition, to ensure the validity of the measured data, every phase was measured ten times.
3 Results

3.1 Microstructure observation

The cross section morphology for Q345 plate cracks position is shown in Figure 1. It shows that there are three obviously different microstructure regions, which are ferrite and pearlite, martensite and bainite respectively. The microstructure for the center of the melt position is bainite, similar to the weld joint. While at the location near the bainite it is martensite and the base metal microstructure is ferrite and pearlite. In addition, it can be seen from Figure 1 that the length of the martensite region marked with double arrow is about 800 μm, beside which they are bainite and ferrite regions with size larger than 1 mm. The bainite region is between the specimen surface and the dot line position. It is apparently different from the previous reported laminated or dispersed dual phase microstructure\[15-16\]. Moreover, Figure 1 also shows that cracks initiated at surface, propagated into the plate interior along the martensite phase and finally terminated at the pearlite and ferrite region where is near to the base metal. Thus, compared to bainite region, the cracks was prone to form between the junction of martensite region and base metal.

![Figure 1. SEM photograph of the specimen cross section with cracks.](image)

Figure 2 shows the large magnification microstructure at different positions along the thickness direction. Figure 2(b), (c), (d), (e), (f) are the microstructures for the position (1) (2), (3), (4), (5) marked in the Fig2(a) respectively. Position (1) and (2) are bainite or sorbite region, position (4) is accordingly the martensite region, position (3) is the phase boundary for bainite or sorbite and martensite, position (5) is the mix microstructure for the pearlite, ferrite and martensite showed in Figure2(f). Combined with Figure1, Figure2 further proved that the crack formed at martensite region and propagated along the martensite zone to the base metal, terminated at region with mix microstructure of pearlite and ferrite. The border of the martensite region near to the base metal is correspondingly the cracks initiation position. Thus, martensite forming should be one of main reason for the occurrence of the cracks.

To further prove the conclusion that the cracks formed at martensite phase region, another crack was observed in Figure 3 which is similar to Figure 1. The crack initiated at the border of martensite region close to base metal side and terminated at the position adjacent to the base metal. In a conclusion, all the results imply that the cracks were prone to form at the region of martensite phase adjacent to base metal during cooling for the Q345 steel plate, which may be caused by the larger hardness variation or larger residual stress between martensite and ferrite in comparison with martensite and bainite or sorbite.
Figure 2. Microstructures for the different positions at the specimen cross section along thickness, (a) low magnification photos of the specimen cross section, (b), (c), (d), (e), (f) represent (1), (2), (3), (4), (5) marked in the Fig2(a) respectively.

Figure 3. SEM photograph of the cracks forming position.

Once cracks formed at plate surface, it will propagate into the interior of the steel plate along a certain path. Figure4 shows the cracks morphologies at different positions. Through
observation of the micro cracks morphologies in Fig 4(a), (b), (c), (d), it can be known that the cracks didn't propagate along prior austenite grain boundary. However, it passed through the martensite block along a certain orientation packet, which means that the cracks always change propagation direction when it propagated from one packet to another packet. Particularly, if the cracks propagate along a packet into another packet which direction does not parallel to it, the cracks will change propagation path direction. Normally, when the cracks met a small packet which is mostly perpendicular to it, the cracks will cross the small packet until it met a larger packet and propagate along the lath boundaries (Figure 4c marked with arrow). It implies that the cracks grow easily and fast in a large block because of no extra resistance for the crack propagation. If the block and the packets are smaller, continuously changing propagation direction for the cracks will slow down the cracks growth rate. Thus, decreasing of the block size and packet size can benefit for hindering of the cracks growth, which is consistent with the reference report [22-23].

![Image](image_url)

Figure 4. The cracks morphologies at different locations.

3.2 EBSD observation

EBSD analysis which can offer orientation distribution for the microstructure were used to investigate cracks propagation path rules. Figure 5 shows the EBSD measured result for the crack tip, in which the middle gray color position represents the crack. The two opposite positions besides the crack are basically same orientation (marked with dot line ellipse) because the crack passed through a packet and split it into two parts. Specially, Figure 5 also shows that there is a crack branch (marked with arrow), but it propagated comparably in a short distance, what’s more, the short branch cracks propagation direction was almost perpendicular to the packet direction. Thus, if the crack grew along this direction, it will continuously cut through several martensite laths during propagation and needs larger force. Comparably, the cracks incline to propagate along the positions where needs small driving force, such as large lath boundaries, packet boundaries, grain boundaries which direction is approximately parallel to the cracks propagation direction. Once the cracks met
a large packet, it will propagate along this packet or deflect to parallel to the packet direction. Similar to the SEM observation results, the EBSD experiment results turns out that the cracks prefer to propagate along larger size packet which almost parallel to the former packet direction. Thus, increasing grain boundary quantity or reducing prior austenite grain size, block size and packet size will benefit for retarding the crack propagation.

3.3 Hardness

Due to different cooling rate at the positions around the melted and cooled 345 steel plate, four types phase formed, which is bainire or sorbite, martensite, ferrite and pearlite respectively. Figure2 shows

That the bainite or sorbite formed at the melted position, beside which is martensite, ferrite and pearlite. Former reports prove that the cracks maybe form for the multi-phase structures because of differences for the phase thermal expansion coefficient and hardness during cooling [24-25]. In order to testify the effect of microstructure hardness on cracks initiation, the hardness for the various phases formed at different positions were measured by the Nano indenter. The measured results were shown in Figure6. Figure6(a) shows the hardness variation with displacement into surface, Figure6b shows the relationship

Figure 6. Curves of the hardness (a) and load (b) with the displacement into surface for the martensite, bainite and ferrite phase respectively.

Curves for the load on sample and displacement into surface. It clearly turns out that the hardness and load for the martensite phase is largest during loading, while the ferrite hardness is smallest. Hardness value at the displacement into surface 700-800nm is selected as the correspondingly measurement hardness. According to the calculation by the software, the average measured hardness for the martensite, bainite and ferrite phase are 5.33GPa, 4.63GPa and 2.85GPa respectively. The larger hardness difference between
martensite and ferrite (2.48 GPa) is the main reason for the crack initiation at the martensite region adjacent to the base metal in this paper compared with melted region and martensite (0.70 GPa).

Table 1. Hardness for different phase.

<table>
<thead>
<tr>
<th>Position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld joint</td>
<td>4.24</td>
<td>5.78</td>
<td>5.51</td>
<td>3.56</td>
<td>3.48</td>
<td>3.38</td>
<td>4.57</td>
<td>5.12</td>
<td>5.85</td>
<td>4.35</td>
</tr>
<tr>
<td>Surrounding Cracks</td>
<td>5.26</td>
<td>5.83</td>
<td>6.07</td>
<td>6.23</td>
<td>5.44</td>
<td>4.93</td>
<td>5.65</td>
<td>5.75</td>
<td>3.92</td>
<td>4.23</td>
</tr>
<tr>
<td>Matrix</td>
<td>2.95</td>
<td>2.46</td>
<td>2.28</td>
<td>2.52</td>
<td>2.46</td>
<td>2.69</td>
<td>3.17</td>
<td>2.95</td>
<td>3.22</td>
<td>3.82</td>
</tr>
</tbody>
</table>

4 Discussion

4.1 Cracks initiation position

Figure 1 and Figure 3 prove that the cracks initiated at the surface of martensite region close to the base matrix or the interface between martensite region and ferrite phase region, but not close to the melted or bainite region. In other words, it is not prone to form cracks at the bonding position of bainite phase and martensite phase as compared to the bonding position of martensite phase and ferrite phase. The hardness result also shows that the hardness variation between martensite and bainite is larger than that of martensite and bainite. The stress concentration increases with the hardness variation between different phase during continuous cooling, which is the main reason that the cracks preferred to forming easily at the interface of the ferrite and martensite compared with that of martensite and bainite. Gou\textsuperscript{[16]} reported that Micro-failure generally occurred in the place with an obvious characteristic of stress concentration. The conclusion of this paper is consistent with the Gou’s result. Moreover, Fig 7 proves that the cracks

![Figure 7](image_url)

Figure 7. The microstructure morphologies surrounding cracks.

Propagate into the ferrite and pearlite matrix, but not along the martensite, which imply that it is difficult for the cracks propagation into harder phase. Once the crack formed, it will propagate along the lower hardness microstructure, because within the harder martensite the inner stress is larger\textsuperscript{[26-27]} and propagation into the harder phase need more extra force. Similar to the inclusions and base metal, if the inclusion hardness is larger, the crack initiate at the interface of the inclusions and base metal, then propagate into the softer base metal but not across inclusions. In a conclusion, the cracks preferentially propagate into the softer phase for the tested material.
4.2 Cracks propagation path

Figure 4 shows that many cracks propagate along the martensite lath in a packet. In order to clarify the cracks propagation path rules, more packets around cracks were observed (Figure 8). It shows that the cracks always propagate along or deflect to the martensite lath direction or packet boundaries. When the cracks propagation direction is perpendicular to the packet direction, it maybe cross the martensite lath in a packet. Figure 8c is the illustration figure for the cracks propagation path. It should be noticed that even the crack met the prior austenite grain boundary, it still propagate along or deflect to the martensite lath direction. The grain boundary is not the prior crack propagation path. The angles for the packet boundaries and grain boundaries were systematically measured by EBSD software. Figure 9 shows the boundary angles distribution at the crack tips within range of 2-10°, 10-30°, 30-50° and larger than 50°. It can be seen that the packet and partial lath boundaries are always larger than 50°. While the ranges for the prior austenite grain boundaries is almost about 30-50 ° (Figure 9c), which is smaller than the packets or partial lath boundaries angles (Figure 9d). Because the larger angle boundaries have larger

![Figure 8. Cracks morphology and its propagation path.](image-url)
Stress concentration or grain lattice distortion, which will reduce the bonding energy for the atoms. Thus, the cracks incline to propagate along the larger angle boundaries. Due to the larger angles for the partial lath and packet boundaries as comparison to the prior austenite boundaries, the cracks prefer to propagation along lath and packet boundaries but not prior austenite boundaries. Particularly, when the cracks propagation directions almost parallel to the martensite lath alignment or packet boundaries direction, the cracks propagation didn’t need more extra energy to change direction and the cracks will preferentially propagate along the lath alignment or packet boundaries. In a conclusion, the experiment results turn out that the cracks are prone to propagation along the lath alignment or packet boundaries, which may be related with the larger boundary angles and small crack forming driving force for the martensite lath and packet.

Local misorientation reflects the residual stress or the dislocation density in the materials. Figure 10 is the local misorientation morphologies around the cracks tip. It shows that the residual stress is larger at the packet and lath boundaries as compared to the other locations. Thus, the cracks inclined to propagate along the packet and lath boundaries, which is consistent with the boundaries angles measurement results. Moreover, the martensite hardness is relatively larger and plastic deformation ability for the martensite is relatively worse, which can promote cracks initiation and propagation. The martensite forming during cooling is the direct reason for the cracks occurrence and its larger hardness lead to the cracks propagation to the softer base metal along lath alignment or packet boundaries with larger boundaries angles. Koyama reports proved the conclusion of this paper, it pointed out that crack propagation path is deflected when propagation across or along different grain boundaries.
4.3 Cracks termination position

Figure 11 shows the cracks termination position with the microstructure of ferrite and pearlite which is close to base metal. There was almost no martensite existence. Though the cracks initiated at the martensite, it propagated and terminated at the softer base metal through continuous deflection of the cracks along packet and lath boundaries during propagation. It also proved that the cracks propagation directions were deflected to lower stress region. Due to the harder martensite occurrence accompanied with larger stress, the cracks initiate at the martensite region. Hence, the experiments further improve that the martensite is the main reason for the cracks occurrence during cooling.

An empirical equation reflect the relation between the nanohardness ($H_n$) and yield strength ($\sigma_y$) as follows\cite{30,31}:

$$\sigma_y = 0.309 H_n$$ (1)

According to the equation (1), it can be concluded that the high yield strength ($\sigma_y$) increases with nano hardness $H_n$. The high yield strength can increase the flow stress. The high flow strength can block the extension of the plastic zone, which made the cracks the propagation into the softer microstructure. In this paper, the martensite hardness is large, while the ferrite hardness is small. Thus, the cracks terminate at the ferrite. Altogether, combined with the nanoindentation tests, it proves that the hardness differences for the different microstructure controlled cracks initiation position and propagation termination position.
It is well known that the inclusions are also one of the factors to cause cracks occurrence during steel fabrication and processing. To further prove that martensite is the main reason for the cracks occurrence, the inclusions around cracks were observed. Figure 12 shows the inclusions in the tested material. It can be seen that there are no cracks initiated around the inclusions (Figure 12b). The composition measured by EDS for the inclusions in Figure 12 is shown in Table 2, which proves that the inclusions are mainly Al₂O₃. The hard and brittle type inclusions incline to be the cracks nucleation cores. However, Figure 1, Figure 2, Figure 12 all proves that the cracks only formed at the martensite region. So the EDS analysis implies that the inclusions is not the reason for the cracks occurrence.

**Table 2.** Compositions for the inclusions made with spectrum 1, 2 and 3 in the Figure 12b.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>C</th>
<th>O</th>
<th>Na</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum 1</td>
<td>0.45</td>
<td>51.16</td>
<td>46.39</td>
<td>0.40</td>
<td>1.62</td>
<td>100.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrum 2</td>
<td>0.45</td>
<td>56.32</td>
<td>41.27</td>
<td>0.82</td>
<td>1.15</td>
<td>100.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrum 3</td>
<td>0.95</td>
<td>31.33</td>
<td>0.48</td>
<td>0.35</td>
<td>0.25</td>
<td>0.36</td>
<td>1.37</td>
<td>64.91</td>
<td>100.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In a conclusion, the martensite and cracks can form easily during cooling. To avoiding cracks occurrence during welding and cooling, it must assure that the cooling rate is small. Decrease of the martensite lath and packet size can retard the cracks propagation.
5 Conclusion

The occurrence of the cracks is related with the harder martensite forming during cooling. For the larger size multi-phase material, the cracks prone to form at the larger hardness difference between different phases. The hardness difference between bainite and martensite (0.70 GPa) is smaller than that of the martensite and ferrite (2.48 GPa), so the cracks initiate martensite phase region where is close to the base metal.

Cracks propagated along the martensite lath and packets boundaries. If the packets direction was perpendicular to the cracks propagation direction, the cracks would pass through the packets until its direction paralleled to the packet or deflect to another packet.

The martensite lath and packets boundaries (larger than 50) which is larger than that of the prior austenite grain (about 30-50). In addition, local misorientation or residual stress for the packets and lath boundaries is larger than other positions. Cracks propagation path is controlled by the boundaries angles. Thus, due to the larger boundaries angles and less boundary amounts for the larger packet martensite, the cracks incline to propagate along or turn to large martensite packets boundaries. Decrease of the martensite lath and packet size can benefit for the hindering of the cracks propagation.

The inclusion is not the main reason for the cracks formed and propagation. The martensite microstructure accounts for the cracks occurrence and propagation.

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

References


