Effect of gradient temperature rolling process on promoting crack healing in Q500 heavy plates

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Abstract: To ensure the quality of heavy plate products as determined by ultrasonic inspection, it is necessary to effectively control defects such as cracks and shrinkage cavities in heavy plates. Generally, some defects such as large size cracks exist due to insufficient deformation in the center of traditionally rolled plates. Compared with the traditional rolling process, gradient temperature rolling (GTR) process can effectively increase deformation inside heavy plates. In this study, the effect of GTR on crack healing was analyzed through a comparison experiment with the uniform temperature rolling (UTR). The results show that the GTR process could increase the plastic strain inside the heavy plate and effectively promote the healing process of the preset cracks. The degrees of crack healing at the center and quarter thickness position of the steel plate via GTR were greater than twice those of the plate via UTR. The GTR process can significantly reduce the internal defects of heavy plates and improve the defect detection level of heavy plate products. Also, The GTR process results in the formation of new crystal grains in the crack region, which is crucial to crack healing.

Keywords: heavy plates; multilayer pack rolling; crack healing behavior; hot rolling process

1. Introduction

Heavy plate is a steel product commonly used in machinery manufacturing, infrastructure construction, marine engineering construction, and other fields. The Z-direction performance and flaw detection level of steel plate are the key indexes to evaluate the quality of heavy plate products. The rolling process of heavy plates and ultra-heavy plates requires continuous casting slabs to be used as rolling billets. However, coarse dendrites and segregation of elements can easily occur in thick casting slabs, and serious defects such as large size inclusion, shrinkage cavities, and cracks are typical disadvantages of the billets. The elimination of defects such as holes and cracks requires considerable strain during hot working. However, the deformation of heavy steel plates produced by the traditional rolling process is concentrated on the surface of the plates. Less plastic strain occurs at the inner position. This would result in the retention of a large number of cracks inside the plate and cause unsatisfactory ultrasonic flaw detection results in the quality inspection stage. These problem will lead to not only the wastage of resources and energy, but also the great economic damage.

In recent years, studies have been conducted on the factors and mechanisms about affecting the healing of defects during thermal deformation, and almost all of the studies emphasize the importance of deformation for the healing of such defects. Yu et al. [1] studied two-layer combination samples compressed under different deformation conditions by thermal compression simulation experiments. The experimental results showed that the deformation temperature, holding time, deformation amount, and deformation rate had significant effects on the healing of preset cracks. Moreover, the deformation degree was greater, the healing degree was higher. Xin et al. [2–4] obtained samples containing preset cracks using a similar segmented rod sample compression method. After observing the microstructure, they summar-
ized the four main stages of crack healing. They believe that recrystallization plays an important role in restoring the strength and impact properties at the cracks. However, it is difficult to completely restore the impact properties. Recrystallized grain growth also homogenizes microstructure and eliminates crack healing areas. Zhang et al. [5] carried out thermal deformation experiments by compressing a cylindrical sample with a drilled hole on Gleeble-1500 thermal simulation experimental machine. The effects of deformation degree, deformation temperature, strain rate, and holding time on crack healing were analyzed. Wei et al. [6] studied the micro-scale process of micro-crack healing in BCC Fe by establishing the molecular dynamics model, indicating that dislocation and voids appeared during crack healing, and their positions were constantly changing. Wei et al. [7] conducted a quasi-in-situ observation using scanning electron microscopy (SEM) and ultrasonic scanning. However, they only evaluated the effects of temperature and holding time on crack healing behavior. Deng et al. [8] set up a finite element simulation of the closing of a core crack in the actual rolling process of ultra-heavy plates. They found that the plastic strain was difficult to penetrate into the center due to the thickness of the heavy steel plate in the first few passes of rolling, and the crack was hard to close. Zhao et al. [9] also used finite element analysis software to study the evolution of the internal holes of the slab during heavy reduction process and rolling. They found that spherical voids will gradually form ellipsoids. The aspect ratio of the voids had a strong correlation with the equivalent strain. The larger the equivalent strain was, the closer the voids were to being flat.

In addition to the thermoplastic deformation method used in the above studies on cracks or holes healing, other treatment methods can also be used under certain specific conditions to heal cracks. Li et al. [10] studied the crack healing behavior of 42CrMo steel by gas nitrocarburizing treatment. Through two-stage high-pressure gas nitrocarburizing treatment at different temperatures, the crack healing degree approached 63.68% maximum. Cavaliere and Silvello [11] used cold spray to repair cracks in aluminum sheets, and the cracked structures of aerospace aluminum alloy panels were effectively repaired. Gunter et al. [12] investigated the crack repairing of 12 mm-thick stainless steel plate via friction stir processing. Grain refinement in some specimens resulted in a much higher stir zone hardness, and some specimens had finer grains in the stirring area than in the matrix. Moreover, the corrosion resistance of the stirring zone was the same as that of the base material. Irrespective of the kind of crack defect repair method, material supplement in a crack area is an indispensable prerequisite for crack healing and repairing.

For the rolling process of heavy plates and ultra-heavy plates, increasing the deformation inside the plate is important, especially near the middle surface of the plate thickness. Nie et al. [13] and Cao et al. [14] respectively obtained 550 MPa and 600 MPa grade heavy plates with a combined production process of thermo-mechanical control, relaxation precipitation control, and accelerated cooling process. The strength and toughness of the steel plate could meet the requirements through grain refinement and precipitation strengthening. This method is effective in refining the microstructure and improving the uniformity of the microstructure and the properties of heavy plates, but a certain amount of alloy elements needs to be added. Accurate control of the relevant parameters in the process is also required.

A novel method called the gradient temperature rolling (GTR) process, presented by Yu et al. [15–19], can generate the gradient temperature field in the thickness direction of the billet before rolling. The deformation in the center of the plate is increased by rolling, and the effect of structure and performance improvement is remarkable compared with that of the common rolling process. The effects of the GTR process on refining microstructure and improving the performance on the center of heavy plates have been comprehensively studied. However, there has been almost no systematic research about the effect of this process on the internal crack defects healing during hot rolling process. In the present work, the effect of this advanced rolling process on the healing of preset cracks in heavy plates was analyzed by experimental methods. The unique crystallization behavior in the crack region was also studied.

2. Experimental

2.1. Materials and billets preparation

The chemical composition of the Q500 steel used for the experiments was 0.11wt% C, 0.3wt% Si, 1.3wt% Mn, 0.4wt% Cr, 0.2wt% Mo, and 0.03wt% Nb.

According to the research on the evolution behavior of internal cracks, there are mainly two methods to preset cracks in the steel billet. One of the methods is overlapping two steel plates after polishing the contact surfaces to be smooth and level. After compaction, the gaps exposed on the lateral surface are welded and sealed. The welding operations are best completed under vacuum to prevent air from remaining between the contact surfaces. The other method is the hole-drilling and compression method. Some through holes or blind holes are drilled on the side of the billet or sample. Then the billet is forged on a hot forging machine to close the hole, which forms internal cracks. In this study, an
experimental method similar to the first mentioned is designed for presetting crack after lamination of multilayer steel plates. The preparation process of the multilayer composite billet is shown in Fig. 1, and Fig. 2 shows the schematic diagram for the structural composition of the multilayer composite billet used in this paper.

2.2. Rolling process

The size of the multilayer composite steel billet was 100 mm (length) × 80 mm (width) × 61 mm (thickness). The physical simulation experiment in the laboratory was carried out based on the similarity law. The billets were rolled using two different rolling processes: the traditional uniform temperature rolling (UTR) process and the GTR process. The schedule of passes for the rolling process is shown in Table 1. Before rolling, the steel plates were heated to 1200°C and kept for two hours to preserve heat. Fig. 3 presents a contrast graph for the temperature distribution of plates in the thickness direction under UTR and GTR processes before rolling.

The plates underwent control cooling to 500°C after rolling. After cooling to room temperature, tensile and metallographic specimens were sampled from the plates. The strengths at different thickness positions inside the steel plates were measured, and the microstructure near the crack was observed using a FEI Quanta FEG scanning electron microscope.

<table>
<thead>
<tr>
<th>Pass No.</th>
<th>Reduction amount / mm</th>
<th>Reduction rate / %</th>
<th>Thickness after pass / mm</th>
<th>Roller rotation speed / (rad·s⁻¹)</th>
<th>Roller diameter / mm</th>
<th>Inter-pass time / s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>8.2</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>7.1</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>9.6</td>
<td>47</td>
<td>3</td>
<td>400</td>
<td>8–12</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>10.6</td>
<td>42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>9.5</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1. Deformation degree at different thickness positions

The billets used for rolling were composed of multilayer steel plates, each layer was about 10 mm-thick. By measuring the average thickness of each layer of the plate after rolling, the relative deformation at different thickness positions could be obtained. From the macrostructure photos of
the plate in the thickness direction (Fig. 4), cracks (marked with numbers) between each layer were visible. The calculation results of deformation degree are shown in Table 2. The total reduction of the steel plate was about 37.7%. For the steel plate rolled via UTR (hereafter referred to as UT-rolled plate), the deformation degree was largest near the surface, and decreased from the surface to the center of the plate. For the plate rolled via GTR (hereafter referred to as GT-rolled plate), the deformation degree was largest at the quarter thickness position, while the deformations at the center and surface were similar. The result verifies that compared with the UTR process, the GTR process can significantly increase the deformation degree at the quarter thickness and the center of a heavy plate.

Table 2. Measurement and statistical results of deformation degree

<table>
<thead>
<tr>
<th>Position</th>
<th>GT-rolled plate</th>
<th>UT-rolled plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close to the upper surface</td>
<td>36.7</td>
<td>45.7</td>
</tr>
<tr>
<td>Upper 1/4 thickness</td>
<td>42.5</td>
<td>37.8</td>
</tr>
<tr>
<td>Upper center</td>
<td>39.3</td>
<td>34.7</td>
</tr>
<tr>
<td>Interior center</td>
<td>35.3</td>
<td>31.7</td>
</tr>
<tr>
<td>Interior 1/4 thickness</td>
<td>36.7</td>
<td>36.5</td>
</tr>
<tr>
<td>Close to the interior surface</td>
<td>35.7</td>
<td>39.8</td>
</tr>
</tbody>
</table>

3.2. Healing degree of preset cracks

Fig. 5 shows the optical microscope metallographic photograph of the healing appearance of cracks at different positions of the plates. Fig. 6 presents the crack microstructure images obtained by SEM. The crack area and healing effect can be clearly distinguished from the figures. The main phase in the crack healing zone was ferrite, and the average size was 10%–20% smaller than that of the matrix. Since the crack was close to the surface of the plate, there is a good healing effect due to large deformation. At the quarter thickness position of the plate, intermittent non-healing bands existed in the UT-rolled plates but not in the GT-rolled plates. The initial crack of the UT-rolled plates developed into elongated oval holes. At the center, the crack healing condition for the UT-rolled plate was worse than that at the quarter thickness. An unhealed crack defect ran transversely through the entire field of view of the metallographic photograph, and the grains on both sides of the crack were rarely in close contact. Apparently, the grains originally located at both sides of the crack did not merge into a whole grain. However, for the GTR steel plate, the previously separated grains in the crack area at the center merged and bonded mostly.

The healing degree of the whole crack in the heavy plate was evaluated according to the following criteria: The appearance of the substantially merged grains across the crack defect was regarded as a healing band. The ratio of the length of the healing band to the total length of the crack was measured, and the statistical results are shown in Table 3. The tensile test data at different thickness positions of the plate are also listed in Table 3. The results presented in the table show that the crack healing degree of the plate via the GTR process was significantly higher than that via the UTR process.

3.3. Crystallization behavior in crack zone

Deletion-type defects such as cracks and holes have mu-
ually separated interfaces. The internal space is usually in a vacuum state. The separated interfaces lack normal chemical bonding among atoms or molecules as well as heat and substance exchange paths. Therefore, the separated interfaces must be brought into physical contact by plastic deformation. Compared with the additive manufacturing process, there is no increase of materials from an external source in the ordinary plastic processing. On a microscopic scale, the supplement of materials is essentially realized by the transformation of the relative positions of atoms. That is, atoms from the matrix fill the defect area through a diffusion process over a long distance. However, it is difficult to eliminate the holes and cracks completely by only the diffusion of atoms.

Fig. 7 shows an observed incompletely healed crack microstructure images obtained by SEM in the center of the UT-rolled plate. The maximum distance between the upper and lower surfaces of the crack was 8.35 μm, and the unconnected interfaces of each grain were approximately in a straight line. There were dome-shaped protrusions of less than 1.1 μm (Fig. 7(b)), and the protrusion on the upper surface was a new crystal grain whose size was much smaller than that of the matrix grain. It can be considered that nucleation of new grains had already occurred when the separation interface spacing was as small as a certain degree. Moreover, there could be a limit to the reduction of the distance between the separated interfaces. After this limit is reached, due to the interaction between atoms and the stress inside the structure, further contraction and elimination of the separation interface must be realized through the nucleation and growth of new grains or the merging of grains. The size
of the newly generated grains is often smaller than that of the matrix grains. This phenomenon is similar to that found in the friction stir processing study of low-carbon steel plates, and refined microstructures also appeared in the friction stir processing area [20]. In the present study, many inclusion particles less than 0.5 μm appeared inside the grains. Some areas with incomplete crack healing had grains with internal holes or holes surrounded by several grains.

In the microstructure of the new crystallization region (Fig. 8(a)), the void size was 1.5–4 μm, and some voids (indicated by the white ovals in the figure) were distributed with continuous thin-film inclusion on their edges, most of which were round or oval. There were also voids (indicated by the white squares) with no inclusion on the edge. Moreover, a large number of small round micro carbide particles with high roundness (indicated by the white circle) were distributed in the grains, with a size of about 0.2–1.5 μm. According to these phenomena, it is inferred that the thin-film inclusion distributed at the edge of the holes will gradually form round and tiny inclusions during the further shrinkage and disappearance of the holes. The residual elongated holes were large in size and surrounded by several grains (Fig. 8(b)). Interestingly, the merged grain featured a tendency of lateral development at its left and right sides (indicated by white arrows). The mechanism was further verified that interface local contact and recrystallization can promote crack healing.

The crack healing process can be generally divided into three stages: closing of separation interface, new grain nucleation, and grain growth and merging. Nucleation of newly generated grains is the most critical condition to achieve

<table>
<thead>
<tr>
<th>Position</th>
<th>Healing degree / %</th>
<th>Yield strength / MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GTR</td>
<td>UTR</td>
</tr>
<tr>
<td>Surface</td>
<td>88.1</td>
<td>88.6</td>
</tr>
<tr>
<td>Quarter</td>
<td>88.9</td>
<td>43.6</td>
</tr>
<tr>
<td>Center</td>
<td>71.2</td>
<td>34.9</td>
</tr>
</tbody>
</table>

Table 3. Crack healing degree and yield strength at different thickness positions of rolled plates

Fig. 6. Crack microstructure SEM pictures at different thickness positions of the plate: (a) close to the surface via UTR; (b) close to the surface via GTR; (c) quarter thickness via UTR; (d) quarter thickness via GTR; (e) center via UTR; (f) center via GTR.
healing. Plastic deformation plays a key role in the above three stages. In the first stage, deformation is needed to move the separated boundary closer and break through the threshold of interface migration and new crystal nucleation. In the second and third stages, a large number of dislocations due to deformation provide a high diffusion rate channel for diffusion [21], it also provides more nucleation sites for newly generated grains [22]. In addition, the deformation storage energy provides energy support for interfacial migration, crystallization, and grain growth.

As the GTR process produced a larger strain at the center of the steel plate than the UTR process, a higher dislocation density and storage energy was generated. The healing process dominated by new grain nucleation and growth in these areas proceeded more thoroughly. Thus, the crack healing in the center of the GT-rolled plate was significantly better than that of the UT-rolled plate.

4. Conclusions

The effect of the GTR process to promote the healing of preset cracks was studied through multilayer rolling experiments for the first time. Crystallization of newly generated grains in the crack area was observed, and the following conclusions were drawn:

(1) According to the results of rolling experiment, when

![Fig. 7. Observed incompletely healed crack microstructure images obtained by SEM in the center of the UT-rolled plate: (a) micro-raised grains before contacting and bonding; (b) newly generated grain.](image)

![Fig. 8. Microstructures images of the new crystallization region (a) and the residual local-merged holes surrounded by several grains (b) in the center of the UT-rolled plate.](image)

the total reduction ratio was 37.7%, the deformation near the surface of the UT-rolled plate was the largest, while that at the center was the smallest. However, the maximum relative deformation of the GT-rolled plate was at the quarter thickness position. The average deformation degree at the center of the GT-rolled plate was 4.1% higher than that of the UT-rolled plate. The results indicate that the GTR process can effectively increase the deformation of heavy plates at the inner position.

(2) Contact between defect separation interfaces is a prerequisite for further healing. The GTR process can speed up the approaching of separated surfaces. Due to the increase of deformation degree, the dislocation density in the tissue is greatly increased, effectively increasing the quantity of atoms diffusing from the matrix to the defect vicinity and shortening the required distance, which will provide a rich material supplement for defect healing. In addition, the increase of deformation energy storage provides energy supplement for crack healing.

(3) The preset crack healing degree in the center and quarter thickness of the steel plate rolled by GTR was significantly better than that rolled by UTR. In the GTR process, no continuous non-healing band but a large amount of newly generated ferrite grains were present in the healing zone. Because of the increase of strain, more nucleation sites and storage energy were provided through the increase of dislo-
cation density so that the nucleation and growth of newly crystallized grains were improved. The special grain crystallization behavior in the crack region plays a key role in promoting crack healing. Further research on the mechanism of this crystallization behavior will be of great significance.

References


