307  高張力鋼板の疲労特性に及ぼす熱処理の影響

Effects of heat treatment on fatigue properties of high tension steel sheets.

O Salleh Tuan Suhaime (佐大工学部) 田村健一 敬信(佐大)
Shin-ichi NISHIDA, Faculty of Science & Engineering, Saga University, ibid.

The fatigue properties are studied in detail on the high-tension steel sheets that are used in automobile structures and components. Safety, durability and stability, as well as good press formability for complicated shapes in automobile industries are necessary for this type of steel sheets. The materials used in this study are 4 types of high-tension steel sheets. The materials are designated as A, Q, T1 and T2 in term of as-rolled sheet, direct quench process and different tempering temperature, respectively. The results show that the fatigue limit is at the highest in material A followed by materials T2, T1 and Q. Compared to material A, the surface hardness in all materials are increased and tensile strength are improved in materials Q and T1 but not in T2. Surface fatigue crack initiation and propagation was studied by the replica methods and their morphology was observed by a scanning electron microscope.

Keywords: High-tension steel sheets, fatigue limit, tensile strength, surface hardness

1. INTRODUCTION

High-tension steel sheet is described as having higher tensile strength than conventional high-strength steel (HSS). This enables the sheet steel to be thinner, yet maintaining the same strength capacity. This steel is used for the ladder frame parts, pillar and rocker panel inner reinforcements, and the inner roof rails in order to reduce the car's weight and ensure safe performance in the event of crash [1]. Lightweight structure enables nimble driving performance and outstanding fuel efficiency. In some car 40% of high-tension steel is used in the body that takes safety to a new level [2]. Safety is a major concern for the chassis, high durability and reliability which are required as well as good press formability for complicated shapes. Therefore the development of the high-tension steel sheets with good press formability and fatigue strength are very important. The fatigue property of the steel is one of the key issues for improvements of the mechanical performance. In this paper, the fatigue behaviors and micro-fracture characteristics of these steel sheets are studied in detail.

2. EXPERIMENT PROCEDURE

2.1. Materials

The materials in this study are 4 kinds of high tension steel sheets and have been thermal treated and machined to the bending fatigue test specimen shape under factory environment. The main chemical composition consists of (wt%): 0.21%C, 0.2%Mn, 1.0%Mn, 0.0015%B and the balance is Fe. All materials were hot working rolled followed by cold working rolled before under going further heat treatment. The final thickness steel sheets are between 1.0mm to 1.24mm. Table 1 lists the mechanical properties and heat treatment conditions of test materials.

2.2. Fatigue test

The applied stress, \( \sigma \), had been determined for each group of the materials according to the Young’s Modulus (E), which were calculated based on the slope of stress-strain diagram. The fatigue test had been conducted using the Shimadzu type bending and torsional fatigue-testing machine with capacity of 49 Nm at constant speed of 2,000 rpm. The sinusoidal waveform loading was uniaxial with a minimum stress ratio, \( R = \sigma_{\text{min}}/\sigma_{\text{max}} = -1 \). The initiation and the propagation of surface’s fatigue crack were studied using the replica method and observed under an optical microscope.

Table 1 The Mechanical properties and heat treatment process

<table>
<thead>
<tr>
<th>ID</th>
<th>Heat treatment conditions</th>
<th>( \sigma_{\text{min}} ) MPa</th>
<th>( \sigma_{\text{max}} ) MPa</th>
<th>U-E1(%)</th>
<th>( \sigma_{\text{max}} )%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>870°C annealing (2 min) ( \rightarrow ) accelerate cooling ( (50^\circ\text{C}) ) ( \rightarrow ) 250°C (5 min) ( \rightarrow ) AC</td>
<td>971</td>
<td>1264</td>
<td>4.9</td>
<td>8.4</td>
</tr>
<tr>
<td>Q</td>
<td>780°C annealing (1 min) ( \rightarrow ) AC ( \rightarrow ) 950°C normalizing ( (5 \text{ min}) \rightarrow ) DQ</td>
<td>1033</td>
<td>1457</td>
<td>4.3</td>
<td>5.9</td>
</tr>
<tr>
<td>T1</td>
<td>780°C annealing (1 min) ( \rightarrow ) AC ( \rightarrow ) 950°C normalizing ( (5 \text{ min}) \rightarrow ) DQ ( \rightarrow ) 250°C tempering ( (1 \text{ hr}) \rightarrow ) AC</td>
<td>1209</td>
<td>1417</td>
<td>3.6</td>
<td>5.2</td>
</tr>
<tr>
<td>T2</td>
<td>780°C annealing (1 min) ( \rightarrow ) AC ( \rightarrow ) 950°C normalizing ( (5 \text{ min}) \rightarrow ) DQ ( \rightarrow ) 400°C tempering ( (1 \text{ hr}) \rightarrow ) AC</td>
<td>544</td>
<td>701</td>
<td>5.9</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Note: AC: air cooling; DQ: direct quenching

3. RESULTS AND DISCUSSIONS

3.1 Fatigue limit, tensile strength and hardness

Generally, the fatigue limit of a material is affected by its microstructure, hardness distribution, residual stress and the experiment condition. In this study, the relationship between the microstructure and hardness distribution was examined. Fig. 1 shows S-N diagram, which is the relationship between stress amplitude \( \sigma_a \) and the number of cycles to failure. The points with arrow showed in this figure are the data for the specimens that did not break even after repeated plain bending stress of 10 million cycles. In the S-N diagram, the horizontal asymptote exists at \( 10^6 \) cycles regime, hence the conventional fatigue limits could be determined. In this study, the fatigue limit of material A is 234 MPa which is the highest, followed by material T2 at 219 MPa, material T1 at 180 MPa and material Q at 167 MPa. Fig. 2 shows the relationship between material in comparison with the fatigue limit of notch specimen, \( \sigma_{\text{fatigue}} \) and calculated fatigue limit, \( \sigma_{\text{fatigue}} \) for plain specimen, tensile strength and surface hardness. The material Q with highest tensile strength has the lowest fatigue strength but the highest surface hardness. Direct quenching process caused this material to become very hard creating the high surface hardness and brittle which affect the fatigue strength. Material A with the second lowest tensile strength has the highest fatigue limit but the lowest surface hardness. The tempering process produces less brittleness microstructures, which is good for fatigue performance. Material T1 obtained low fatigue limit and low surface hardness but with quite high tensile strength. Heat treatment performed for

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this material is the same as $Q$ material and added with further tempering treatment at 250 °C for one hour which caused martensite structures to become less brittle creating low hardness. Material $T2$ shows the lowest tensile strength with further tempering treatment at 400 °C for 1 hour. The carbon trapped in the martensite transformation can be released by heating the steel below the A1 transformation temperature. This release of carbon from nucleated areas allows the structure to deform plastically and relieve some of its internal stresses. This reduces hardness and increases toughness, but it also tends to reduce tensile strength. This result shows that the degree of tempering is dependent on temperature and time, here temperature being the largest influence. Tempering also increases softness, ductility, malleability, and impact resistance which create a better combination of fatigue strength and surface hardness. From the observation explained above, tensile strength is not proportional to the fatigue limit, which means the highest tensile strength does not absolutely show the highest fatigue limit. In this case, the ultimate elongation and/or total elongation during tensile have important roles in affecting the fatigue limit especially for materials $T2$ and $A$. Total elongation relative to elastic elongation i.e. percentage of elongation could be reached without permanently deforming and as indicator to material ductility. With high ductility, material has ability to withstand plastic deformation without failure and as in fatigue test, it required high stress amplitude to create plastic deformation prior to slips band which induces crack initiation.

### 3.2 Fatigue limit of plain specimens

In present study, only fatigue limits of notch specimens have been obtained. However, fatigue limit of plain specimens could also be theoretically calculated. In order to raise the confidence, an average of fatigue limit ($\sigma_{fl}$) is obtained from two different calculation methods and has been selected as the fatigue limit of plain specimens. The overall results are listed in Table 2.

<table>
<thead>
<tr>
<th>ID</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>Hv</th>
<th>$\sigma_n$</th>
<th>$\sigma_{fl}$</th>
<th>$\sigma_{ult}$</th>
<th>$\sigma_n$</th>
<th>$\sigma_{ult}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>2.68</td>
<td>2.60</td>
<td>194</td>
<td>234</td>
<td>627</td>
<td>608</td>
<td>618</td>
<td>1264</td>
</tr>
<tr>
<td>$Q$</td>
<td>2.68</td>
<td>2.60</td>
<td>450</td>
<td>167</td>
<td>448</td>
<td>434</td>
<td>441</td>
<td>1457</td>
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<tr>
<td>$T1$</td>
<td>2.68</td>
<td>2.60</td>
<td>204</td>
<td>180</td>
<td>483</td>
<td>468</td>
<td>476</td>
<td>1417</td>
</tr>
<tr>
<td>$T2$</td>
<td>2.44</td>
<td>2.50</td>
<td>354</td>
<td>219</td>
<td>535</td>
<td>548</td>
<td>540</td>
<td>701</td>
</tr>
</tbody>
</table>

$\alpha = 2.762$

**Note:** $\sigma$: stress concentration; $\sigma_m$: notched fatigue limit; $\sigma_n$: tensile strength; $\beta_1$, $\beta_2$: fatigue notch factors; $\sigma_{fl}$, $\sigma_{ult}$: calculated plain fatigue limit; $\sigma_{ult}$: an average plain fatigue limit.

### 3.3 Initiation and propagation fatigue cracks

The nominal stress amplitude by 250 MPa was applied to investigate the crack behavior of all materials. Materials that were used to study surface cracks through replica sampling were also used to study fracture surface using a scanning electron microscope (SEM). The observations results are; Due to the ductility condition belong to material $A$ the $N/N_r$ ratio of crack initiation is 0.53 which is considered to be high value. Material $Q$ with $N/N_r$ ratio is 0.19 and this ratio is low probably due to brittleness of material has the highest surface hardness. $N/N_r$ ratio for material $T1$ is 0.16 and is considered the lowest even though the brittleness of this material is less than material $Q$. This situation probably relates to the lower surface hardness belong to this material which would create slips rather easy prior to crack initiation. In addition the $N/N_r$ ratio of material $T2$ could not easily be confirmed because at $N = 6.9 \times 10^4$ cycles the crack is already long. The replica samples at $N = 6.6 \times 10^4$ cycles however has no crack initiation identified even when inspected under high magnification microscope focusing. The $N_r$ for this material is $9.6 \times 10^2$ cycles. After this consideration, the earliest crack was probably initiated between $N = 6.6 \times 10^7$ cycles and $N = 6.9 \times 10^4$ cycles or $N/N_r$ ratio is between 0.69 to 0.72. This could be caused by high ductility and good surface hardness belonged to this material that exists after heat treatment was being applied. In addition, as the microstructure of this material is dispersed fine tempered martensite form, this condition also resist the propagation of fatigue crack [3]. In other words, life is extended and fatigue strength rate increases as the initiation of cracks is suppressed [4]. Basically the fracture surfaces in all materials included voids and inclusion. The striation mode was found in fracture surface of material $A$ with voids and some inclusion. In material $Q$ the crack was initiated due to existing of inclusions and there are some voids between grain structures which caused lack fatigue strength [5,6]. In material $T1$ some inclusions were observed to induce fatigue crack initiation, the voids within material structures were found which also could cause fatigue crack. These two possibilities may be able to assist and decide the actual place where the fatigue crack was initiated. In material $T2$ with agreement of replica sample and based on the wide smooth fracture, there are no doubts that the fatigue crack was initiated due to inclusions existence. The fatigue strength of this material could probably be increased in no inclusion condition. At the fracture area there were also some inclusions exist, hence reduces the fatigue performance.

### 4. CONCLUSIONS

1. Heat treatment applied in this study did not contribute to the highest values of the three mechanical properties combinations, tensile strength, fatigue limit and hardness.
2. Material $T2$ shows good combination of fatigue strength and surface hardness. Although lack in tensile strength it shows better ductility properties based on the fatigue crack initiation measured by the $N/N_r$ ratio with respect to crack length and fatigue crack growth rate.
3. Tensile strength is not a main factor in influencing fatigue limit as ductility is also a factor which can be evaluate based on materials' elongation habits.

**References:** omitted