QUENCHING CRACK ANALYSIS OF BIG SIZE FORGING BY FE ANALYSIS

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ABSTRACT

Heat treatment crack is one of the main defects of big size forging manufacturing process. In this research finite element method has been applied to predict crack initiation by mass effect during water agitation cooling. Cooling curve of specimens was measured water quenching test and convective coefficients were calculated by inverse method based on finite element method. Water quenching processes were analyzed by Deform software and Jmatpro. Crack initiation has been predicted by comparison of stress distribution and strength on the temperature basis.

Key words: Quenching Crack, Big size forging, Crack initiation prediction, Finite element analysis, Quenching direction.

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1. INTRODUCTION

Big size forging is widely used for heavy industries such as ship building, petrochemical component, wind turbine etc. The weight of open die forging is over 10 tons to 200 tons and mechanical properties is mainly affected by cooling speed. But cooling speed of internal region in big size forging is so extremely slow that mechanical properties of forging is deteriorated due to mass effect. Moreover, cooling speed difference between surface and internal region generates residual stress which induces quenching crack.

Quenching crack is old topics in heat treatment process and lots researches have been conducted to verify the reasons of quenching cracks.

Kobasko[1] performed quenching test for medium carbon steel, low alloyed steel and 0.82% carbons steel on various shaped specimens with various cooling speed. He insisted 300 - 350°C/s cooling speed showed maximum crack probability and changing cooling speed reduced quenching crack. Gur[2] applied finite element analysis method to predict temperature field, volume fraction of phases and the evolution of internal stress states during quenching. The analyses were compared with case studies of St50, Ck45 and C60 of solid and hollow components. Arimoto[3] tried to establish quenching crack criterion by finite element analysis and test for tool steels. Gang[4] tried to establish quenching crack prediction model with phase transformation and internal stress and strain field during quenching process. They
concluded that analytical method gave useful data for the design, control and quenching process optimization but phase transformation and convective heat transfer coefficient for different cooling method cannot be accurately predicted. Chen[5] tried to increase mechanical properties preventing quenching crack by selecting cooling method for big size forging. He performed parameter studies using finite element method. Gallina [6] adopted finite element method to predict crack formation by quenching considering microstructure evolution during quenching process and compared with actual component.

Previous researches generally focused on stress field and temperature distribution by finite element method and comparison with actual component. In this research, finite element method has been also adopted to calculate local stress distribution coming from heat treatment and yield strength and tensile strength according to temperature drop is calculated by Jmatpro 6.0. The comparison between stress and strength enables crack initiation prediction.

2. COOLING COEFFICIENT CALCULATION

2.1. Quenching Test

Cooling test block is manufactured with SCM440 by forging at the size of 300 x 600 x 300mm and thermocouples are attached at the 2 point to measure temperature distribution by water quenching. Test block and thermocouple location are described in Figure 1.

The test block has been heated to 910℃ and held in 3 hrs and then cooled down in the 40℃ water. The cooling curve of each location is shown in Figure 2. Point (b) location in the internal region shows cooled down slowly than Point (a)

![Figure 1 Dimension of cooling specimen and thermocouple location](image)

2.2. Convective Heat Transfer Coefficient of Water cooling

Cooling phenomenon can be modeled by convection cooling between specimen and water. Heat transfer coefficients can be calculated by repeated finite element method so called inverse method. The Inverse Heat Module of Deform 3D was applied to calculate the cooling heat transfer coefficients by inverse method for quenching process. The basic thermo-mechanical properties for heat transfer analysis can be calculated using chemical composition of SCM440 by Deform Software. The chemical composition and thermo-mechanical properties are shown in Table 1 and Figure 2.
Table 1 Chemical composition of SCM440 test block

<table>
<thead>
<tr>
<th></th>
<th>C (%)</th>
<th>Si (%)</th>
<th>Mn (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Cu (%)</th>
<th>Ni (%)</th>
<th>Cr (%)</th>
<th>Mo (%)</th>
<th>Al (%)</th>
<th>V (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results</td>
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<td>0.30</td>
<td>0.87</td>
<td>0.010</td>
<td>0.001</td>
<td>0.08</td>
<td>0.08</td>
<td>1.11</td>
<td>0.25</td>
<td>0.034</td>
<td>0.058</td>
</tr>
</tbody>
</table>

Figure 2 Thermo-mechanical properties of SCM440

Mesh system and heat transfer analysis with thermo-mechanical properties are shown in Figure 3.

Figure 3 Mesh system and heat transfer analysis

Figure 4 shows the comparison of experimentally measured temperature distribution of each location and analyzed temperature by Deform 3D. The calculated temperature of internal region (point b) is quickly cooled down to experiment. The analyzed temperature of surface (point a) is slowly cooled down comparing to experiment temperature.
Convective heat transfer coefficient calculated by Deform 3D Inverse module is shown in Figure 5. The heat transfer coefficient is low at the 910°C because of bubbling phenomenon of cooling surface. The coefficient is steadily increased up to 380°C and decreased to room temperature.

3. FINITE ELEMENT ANALYSIS OF QUENCHING PROCESS

3.1. Forging Product with Quenching Crack

This research focuses on the analysis of the reason of quenching crack with finite element method. The target product is gear rims for ship building weighing 27 tons with quenching cracks. Figure 6 shows the surface cracks occurs in quenching process in the internal bore area.

3.2. Stress Analysis in Quenching Process

Finite element analyses were conducted for crack generated product to evaluate stress levels in high temperature during quenching process. Heating temperature is 890°C and forging is cooled down in the water chamber. Thermo-mechanical properties of SCM440 and convective thermal coefficient is applied to finite element analysis. Mechanical properties of SCM440 is elasto-plastic condition to analyze stress distribution during quenching process. The shape of forging and mesh system for finite element analysis are shown in Figure 7.
Temperature distribution of cracked shape and alternative shape are compared for crack generated area. The temperature of crack generated area at point 1 at Figure 8(a) is slowly cooled down compared to other area (point 2, point 3 and point 4 at Figure 8(b)) due to shape effect. The temperature gradient for surface are shown Figure 8(c).
Temperature distribution of big size forging generates local stress field due to cooling speed and temperature difference. The stress distribution of forging by elasto-plastic analysis analyses is shown Figure 8(d). Stress distributions on time for point 1 and point 3 corresponding to crack generated region are extracted with point tracking method. The principal stress at point 2, point 3 and point 4 are increased stiffly within 20 after quenching and reduced quickly 30 seconds after quenching. After then stress shows slow reduction trend to negative value. But The principal stress at point 1 is increased steadily up to 260 MPa until 70 seconds then reduced same way at 300 seconds.

Yield stress during cooling process is deeply related to cooling rate and temperature. The cooling speed of point 1 is calculated to 2°C/s and point 2, point 3 and point 4 is 25°C/s respectively. 0.2% Offset strength for temperature is calculated with Jmatpro 6.0 for the cooling rate of 2°C/s and 25°C/s and shown Figure 9(a). The comparison between local principal stress and yield stress is made for point 1 and point 3. If local principal stress exceeds yield stress, crack initiate. The principal stress and yield stress distribution for point 1 and point 3 is shown Figure 9(b). The principal stress exceeds 0.2% offset strength

(a) 0.2% Offset strength according to cooling speed

(b) Principal stress distribution at the crack generated region

**Figure 8** Temperature gradient of crack location of quenching process
Figure 9(b) explains the generation of crack during cooling process for original shape. The principal stress of point 1 exceed 0.2% offset strength from 20 to 90 seconds. But local principal stress of point 3 does not exceed 0.2% offset strength at all time.

4. CONCLUSIONS

In the present work cooling experiments for forging blocks in water chamber were conducted to find the convective heat transfer coefficient. The cooling coefficient was calculated by inverse module of deform 2D software. The elasto-plastic finite element analysis was conducted to investigate temperature and stress distribution of big size forging of which the quenching crack was generated during quenching process. The principal stress exceeds 0.2% offset strength of 2°C/s cooling rate at the crack initiated area. The same analysis result applied to shape modified forging showed cooling speed was uniform and principal stress does not exceed yield stress. The quenching test with modified shape was conducted and there was no crack in the bore. This research validated stress analysis approach with temperature dependent 0.2% strength to predict quenching crack with finite element analysis.

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