Finite element analyses of TMCP steel plates with consideration of edge masking

Dung-An Wang\textsuperscript{a,\#}, Wei Lo\textsuperscript{b}, Yhu-Jen Hwu\textsuperscript{b}

\textsuperscript{a}Graduate Institute of Precision Engineering, National Chung Hsing University, Taichung 40227, Taiwan ROC
\textsuperscript{b}Iron & Steel Research & Development Department, China Steel Corporation, Kaohsiung 81233, Taiwan ROC

Abstract

Complex thermal stress and distortion are inevitably generated in TMCP (thermo-mechanical controlled process) steel plates. The excessive distortion due to uneven cooling may be detrimental to the integrity of TMCP steel plates. To improve the uniformity of TMCP steel plates, they are partially masked near the edge of the plate in the water spraying cooling process. In order to assist process engineers to select appropriate edge masking amounts, the effects of the edge masking amounts on thermal stress and distortion of TMCP steel plates are investigated by finite element analyses. Scheil’s additivity rule and Johnson-Mehl-Avrami-Kolmogorov (JMAK) model are considered in the phase transformation model of the thermo-elasto-plastic finite element program. The effects of edge masking on the distortion of the TMCP plates are presented.

© 2013 The Authors. Published by Elsevier Ltd. Selection and/or peer-review under responsibility of the Paper Review Committee of CTAM 2013.

Keywords: Thermomechanical controlled process; finite element analysis; distortion.

1. Introduction

TMCP steel plates are produced by rolling followed by accelerated cooling or in-line direct quenching in order to obtain high strength, high toughness and good weldability [1]. The high strength and toughness can be attributed to the fine and uniform acicular ferrite microstructure in TMCP steel [2]. The accelerated cooling process results in complicated thermal stress and distortion in TMCP steel plates. In order to maintain dimensional and shape accuracy, it is critical to control the uniformity of cooling during the process. The plate’s edges were masked during the accelerated cooling step for improvement of the temperature uniformity of the TMCP steel plate. It may take months or years for engineers to find out appropriate edge masking amounts to decrease the distortion of the TMCP plates. Simulation tools are needed to accelerate the pace of understanding the mechanics behind the process and the search for processing parameter to achieve high flatness of the TMCP steel plates.

The distortion of the TMCP steel plates is investigated by finite element analyses in this paper. Scheil’s additivity rule and Johnson-Mehl-Avrami-Kolmogorov (JMAK) model are considered in the phase transformation model of the thermo-elasto-plastic finite element program. The distortion of the TMCP steel plates after the accelerated cooling process, air cooling process and springback are examined. The effects of the amounts of the edge masking on the distortion of the TMCP plates are studied. The optimal amount of edge masking to reduce the distortion of TMCP steel plates can be determined based on the developed program.
Fig. 1. (a) Schematic of a steel plate. (b) Masked surfaces of the plate.

Fig. 2. (a) A schematic of the half steel plate. (b) A finite element mesh of the half model. The edge masking region is divided into seven zones for future investigation of the effects of uneven edge masking on the shape uniformity of the TMCP steel plates.
2. Model

Fig. 1(a) schematically shows a TMCP steel plate with edge masking conditions. A Cartesian coordinate system is also shown in the figure. The surfaces masked for reduced cooling is shown by gray region. The plate has the thickness \(T (= 0.025\text{m})\), the width \(W (= 3.6\text{m})\), the length \(L (= 10.5\text{m})\), and the width of edge masking \(M\). The masked surfaces are shown in Fig. 1(b). In order to investigate the mechanics behind distortion mode of the TMCP steel plate during the accelerated cooling process and to systematically examine the effects of the amount of edge masking on the distortion of the plate, three-dimensional finite element analyses are carried out.

The problem is symmetric about a \(x-y\) plane through the center of the plate, and only half of the plate is modeled. Fig. 2(a) is a schematic of a half model. Fig. 2(b) shows a finite element mesh of a half plate. A Cartesian coordinate system is also shown in the figure. As shown in Fig. 2(a), the displacement in the \(z\) direction of the symmetry plane, the \(x-y\) plane, is constrained to represent the symmetry condition due to the temperature loading conditions and the geometry of the plate. Neumann boundary condition is applied at the symmetry plane of the specimen and a heat flux \(q = 0\) is introduced. Fourier boundary condition with heat convection and radiation is applied at the water spraying surfaces and at the edge masking surfaces (reduced amount of water spraying) of the plate. The initial temperature of the specimen is taken as 800 °C, and the temperatures of the water and air are taken as 20 °C. To model the effects of edge masking, the convection heat transfer coefficients of the water in the edge masking region are multiplied by a factor of 0.3 of the free convection heat transfer coefficients of water listed in Table 1.

<table>
<thead>
<tr>
<th>(T [\text{°C}])</th>
<th>(h_c [\text{W/m}^2\text{°C}]) of free convection for water</th>
<th>(h_c [\text{W/m}^2\text{°C}]) of free convection for air</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4350</td>
<td>5</td>
</tr>
<tr>
<td>200</td>
<td>8207</td>
<td>25</td>
</tr>
<tr>
<td>300</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>400</td>
<td>11962</td>
<td>50</td>
</tr>
<tr>
<td>430</td>
<td>13492</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>12500</td>
<td>-</td>
</tr>
<tr>
<td>560</td>
<td>10206</td>
<td>-</td>
</tr>
<tr>
<td>600</td>
<td>7793</td>
<td>75</td>
</tr>
<tr>
<td>700</td>
<td>2507</td>
<td>90</td>
</tr>
<tr>
<td>800</td>
<td>437</td>
<td>110</td>
</tr>
<tr>
<td>900</td>
<td>135</td>
<td>-</td>
</tr>
<tr>
<td>1000</td>
<td>-</td>
<td>175</td>
</tr>
</tbody>
</table>

The material of the steel plate is S50C steel and is modeled as an elasto-plastic, isotropic material. The typical values of the Young’s modulus, Poisson’s ratio, yield strength, strain hardening exponent, coefficient of thermal expansion, density, thermal conductivity and specific heat of various phases of steel are taken as functions of temperature. The commercial finite element program ABAQUS is employed to perform the computations. The displacement and temperature element, C3D8T, is used. The user subroutines UMAT, UEXPAN and UMATHT are coded into the finite element program to define the material thermal and elasto-plastic behaviors. The three-dimensional finite element model for the steel plate has 4,620 8-node brick elements.

3. Analyses and discussions

A significant amount of distortion occurs after the cooling process of the TMCP plates. The thermomechanical analyses are performed in two steps: step 1 the accelerated cooling process of 7 seconds and step 2 the air cooling process of 200 minutes. The water convection on the unmasked surfaces and the reduced water convection on the masked surfaces are applied in the first step of the analysis. Six values of the width of edge masking \(M\), namely, 60 mm, 120 mm, 180 mm, 240 mm, and 300 mm, are considered, corresponding to the ratios of \(M/W\), 0.033, 0.067, 0.1, 0.133, and 0.167. The case without edge masking is also considered. In the second step of the analysis air convection is applied on all surfaces of the plate.
Fig. 3. Displacements of the nodes on the front surface as a function of the distance from the symmetry axis (a) after the accelerated cooling step; (b) after the air cooling step.

Fig. 4. Displacements of the nodes on the side surface as a function of the distance from the rear surface (a) after the accelerated cooling step; (b) after the air cooling step.

Fig. 5. A photo of a TMCP steel plate.
Fig. 3(a) shows the displacements of the nodes on the front surface as a function of the distance from the symmetry axis after the accelerated cooling step. The front surface, the rear surface, the side surface and the symmetry axis are indicated in Fig. 2(a). The results show a progressive increase in the displacement in the masked region as the width of the edge masking increases. The displacements increase steeply at the interface between the unmasked region and the masked region. After air cooling, the displacements of the nodes on the front surface with edge masking decrease significantly except for the case without edge masking (see Fig. 3(b)). Fig. 4(a) shows the displacements of the nodes on the side surface as a function of the distance from the rear surface after the accelerated cooling step. The displacements of the cases with edge masking are much lower than the case without edge masking. As the width of the edge masking increases, the displacement increases initially, drops, then increases, drops again. The displacement is not correlated with the amount of edge masking bases on the computations. Fig. 4(b) shows the displacements of the nodes after air cooling. The displacements of all cases decrease considerably. It appears that the cases with edge masking have much lower displacements than the case without edge masking. The case with edge masking of 60 mm performs much better than the other cases with edge masking. Fig. 5 is a photo of a TMCP steel plate with a length of 11 m, a width of 3.675 m and a thickness of 0.028 m, where the width of edge masking is 100 mm. The computational results seem to be able to predict the curled-up shape near the front and rear end of the plate (see Fig. 4 and Fig. 5).

![Deformed shape along front edge](attachment:front_edge_displacement.png)

Fig. 6. Displacements of the nodes on the front surface as a function of the distance from the symmetry axis after the springback step in the case of edge masking of $M = 300$ mm.

![Deformed shape along outside edge](attachment:outside_edge_displacement.png)

Fig. 7. Displacements of the nodes on the side surface as a function of the distance from the rear surface after the springback step in the case of edge masking of $M = 300$ mm.
The phenomenon of springback may occur after the air cooling process, because the steel plate is very thin and flexible. The springback analysis is performed after the air cooling process, and a static analysis calculates the springback. During the static analysis an artificial stress state that equilibrates the stress state after the air cooling process is applied automatically by Abaqus and gradually diminished. The amount of springback is measured as the displacement obtained at the end of the step, and the stresses give the residual stress state [3]. Fig. 6 shows the displacements of the nodes on the front surface as a function of the distance from the symmetry axis after the springback step in the case of edge masking of \( M = 300 \) mm. Fig. 7 shows the displacements of the nodes on the side surface as a function of the distance from the rear surface after the springback step in the case of edge masking of \( M = 300 \) mm. The analyses show the plate is not likely to spring back after the air cooling step in the width direction (see Fig. 6) and in the length direction (see Fig. 7). The stress states might have been equilibrated during the long air cooling step of 200 minutes. Nevertheless, in order to obtain better prediction of the distortion of TMCP steel plates, the effects of springback should be included in the simulations. A better simulation of the distortion of the TMCP plates would be achieved by using several elements through the thickness of the plates.

Initial stress after hot rolling process is not considered in the investigations. Wang et al. [4] reported that residual stress in hot rolled steel strip is an important parameter to influence the flatness of the strip during the cooling process. The initial stress before the accelerated cooling process should be considered in order to improve the accuracy of the developed finite element program.

4. Conclusions

This paper presented a computational study of the distortion of a TMCP steel plate. The thermomechanical behaviors of TMCP steel plates during accelerated cooling, air cooling and springback can be analyzed by the developed finite element program. The program has a potential to be used as a tool to predict qualitatively the deformation and residual stress of TMCP steel plates. More thorough experiments need to be carried out to prove the applicability of the program.

Acknowledgements

This work is funded by China Steel Corporation under grant RE101019.

References