Prediction of Mechanical Properties of TRIP Steels by FEM and Micromechanics

Jin Ho Bae¹, Seong-Jun Park¹, Kyu Hwan Oh¹, Chang Gil Lee² and Sung-Joon Kim²

¹School of materials Science and Engineering, Seoul National University, Seoul 151-742, Korea
²Korea Institute of Machinery and Materials, Kyunsangnam-Do, 641-010, Korea

KEY WORDS : Transformation induce plasticity, TRIP steel, retained austenite, finite element code, finite deformation theory, self-consistent method, mechanical property

Abstract

The effect of shape and volume fraction of retained austenite on the uniaxial behavior of transformation induced plasticity(TRIP) steels was studied by using the numerical and experimental methods. 0.16%C-1.4%Si-1.4%Mn TRIP steels were intercritically annealed at 800 °C and 840 °C, and isothermally transformed at 450 °C (Banite Transformation) during 1, 5 and 10 min. As the bainite isothermal transformation time increased, the volume fraction of retained austenite, tensile stress and total elongation decreased, and 0.2% yield stress increased. Finite element method calculations were carried out by using ABAQUS user subroutine UMAT based on the finite deformation theory and self-consistent method. Numerical results were in good agreement with experimental data.

1. Introduction

In high Si and Mn steels, the transformation of retained austenite to martensite due to deformation significantly strengthens and increases ductility, which is well known as Transformation Induced Plasticity(TRIP) phenomenon[1]. The production of TRIP steels with higher strength and better formability has been one of the important subjects in recent steel technology[2,3]. To achieve this goal, it is necessary to understand the basic mechanism of the TRIP phenomenon. Stringfellow[4] analyzed the effect of stress state into the strain induced transformation kinetics which is proposed by Olson and Cohen[5].

The present work was conducted to investigate the effects of shape, volume fraction and stability of retained austenite on the uniaxial behavior of 0.16%C-1.4%Si-1.4%Mn TRIP steels. By using the micromechanical model by Stringfellow, the finite element code, based on the finite deformation theory and self-consistent method, was developed. To consider the effect of microstructure on mechanical properties, the unit cell model was adopted. The calculated stress-strain curve and volume fraction of martensite were compared with experimental results.

2. Experimental Procedure

Table 1 shows the chemical composition of the steel used in this study. The steel was melted in vacuum, followed by hot forging into 25mm thick plate. At 1250 °C the plate was hot rolled to 3mm thickness, finished at 900 °C and air cooled. After cold rolling to 1mm thickness, the tensile specimens with 25.4mm gauge length by 6.3mm width parallel to the rolling direction were machined. The tensile specimens were heat treated to obtain various volume fraction of retained austenite. Fig. 1 shows the heat treatment cycle. The cold rolled specimens were annealed at 800 °C and 840 °C for 5 min(Intercritical annealing), followed by isothermal transformation(Banite transformation) at 450 °C for 1, 5 and 10 min, and air cooling. The holding times at intercritical annealing and bainite transformation temperature determine the
Table 1. Chemical composition of steel in this study (wt %)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>1.42</td>
<td>1.47</td>
<td>0.0016</td>
<td>0.0036</td>
<td>0.046</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic diagram of heat treatment schedule

volume fraction of retained austenite. Image analyzer (BMM PLUS) was used to obtain the volume fractions of the ferrite and bainite, and the volume fraction of optically undistinguished retained austenite was determined by the X-ray diffraction using Mo-Kα radiation[6]. Carbon concentration in retained austenite was determined from diffraction peaks (200), (220) and (311) of Cu-Kα radiation[7].

3. Constitutive equation

Olson and Cohen proposed a kinetic model to describe strain induced martensitic transformation[5], and Stringfellow modified the kinetic model to take into account the effect of stress state[4]. The rate of increase in the volume fraction of martensite, \( \dot{f} \), can be expressed by

\[
\dot{f} = (1 - f) (A_f \dot{\gamma}_a + B_f \Sigma)
\]

where, \( A_f = \alpha \beta_0 r (1 - f_{sb}) (f_{sb})^{-1} P \), \( f_{sb} = 1 - e^{-\alpha \gamma_a} \), \( \Sigma = -p / \sqrt{3} \tau \), \( \dot{\Sigma} = (\dot{p} / p - \dot{\tau} / \tau) \)

\( \dot{\gamma}_a \) is the shear strain rate in austenite, \( f_{sb} \) is the volume fraction of shear band, \( \beta_0 \) and \( r \) are geometric parameters, \( P \) is the probability that the shear band intersection will act as a nucleation site, \( \alpha \) is the rate of shear band formation at low strain. \( p \) is pressure, \( \tau \) is equivalent shear stress and \( \Sigma \) can be a measure of the triaxiality of the stress state. \( \dot{p}, \dot{\tau} \) and \( \dot{\Sigma} \) is the rate of \( p, \tau \) and \( \Sigma \), respectively. To obtain the plastic strain rates of martensite and austenite, the Eshelby’s solution[8] for the spherical inclusion(martensite) embedded in an infinitely extended matrix(austenite) was used.

To describe the micromechanical stress-strain relation, the viscoplastic material model was used.

\[
\frac{\dot{\gamma}}{\dot{\gamma}_0} = \left( \frac{\tau}{\tau_0} \right)^M
\]

where \( \tau_0 \) is a reference shear stress, \( \dot{\gamma}_0 \) is a reference strain state and \( M \) is a rate sensitivity.

Table 2. Material parameters used in FEM analysis

<table>
<thead>
<tr>
<th>Young’s modulus(GPa)</th>
<th>Poisson’s ratio</th>
<th>( \alpha )</th>
<th>( \beta_0 P )</th>
<th>( r )</th>
<th>( M )</th>
<th>( \dot{\gamma}_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
<td>0.3</td>
<td>8</td>
<td>4.2</td>
<td>3.8</td>
<td>10</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Material parameters in the FEM calculation are shown in Table 2. In Table 2, martensite
evolution parameters $\alpha$, $\beta$, $P$ and $r$ were chosen to give the best fit to the martensite volume fraction with increasing tensile strain.

4. Computational Method
4.1. Numerical Procedure
The model described in previous section was implemented into the finite element code ABAQUS by using user supplied subroutine UMAT[9]. Euler backwards difference operator and the method of radial return[10] were used to obtain the convergence of stress state. A material Jacobian was used to achieve an accurate assessment of the incremental kinematics in global Newton scheme.

4.2. Stress-Strain Curves of Constituent Phases
In order to express the stress-strain relations of ferrite, bainite and martensite, the following Swift’s equation was used.

$$\sigma = a(b + \varepsilon_p)^N$$

where $\sigma$ and $\varepsilon_p$ are the equivalent stress and equivalent plastic strain, respectively. Material parameters, $a$, $b$ and $N$ were expressed by chemical composition, microstructural parameters and suitable process parameters[11]. Calculated values of $a$, $b$ and $N$ are shown in Table 3.

5. Result and Discussion
5.1 Microstructure and Mechanical Properties
Fig. 2 shows the measured tensile stress, 0.2% yield stress and total elongation as a function of bainite isothermal transformation time. As the bainite isothermal transformation time increases, 0.2% yield stress increases, but tensile stress and total elongation decrease. Tensile stress and 0.2% yield stress of steels annealed at 840 °C are higher than that at 840 °C, and total elongation is smaller.

Fig. 3 (a) and (b) show the optical micrographs of the steels intercritically annealed at 800 °C and isothermally transformed at 450 °C during 1 min and 10 min, respectively. The heat treated structures are composed of polygonal ferrite(white), bainite and retained austenite(gray). The shapes of bainite and ferrite kept unchanged with increasing isothermal transformation time.

Fig. 4 shows the variation of volume fraction and carbon content of retained austenite as a function of the bainite holding time. The increase of the bainite transformation time from 1 to 10 min at 450 °C give rise to the decrease of both volume fraction and carbon content of retained austenite as shown in Fig. 4. At the beginning of isothermal transformation, the carbon content in retained austenite increases due to the carbon rejection from bainitic ferrite. And the increase of the holding time resulted in the carbon enrichment in the austenite, leading to the formation of fine precipitated carbide and the decrease of the volume fraction and carbon content of retained austenite[12].

As can be seen in Fig. 2 and Fig. 4, the maximum volume fraction and carbon concentration of austenite coincide with the maximum total elongation and tensile stress of steels. The martensite induced by deformation of steels depresses the occurrence of necking and increases the resistance of steels to deformation. The steel with maximum volume fraction of austenite has the maximum value of total elongation and tensile stress. But the tensile stress is less influenced than total elongation and 0.2% yield stress by the volume fraction of retained austenite. As the bainite transformation time increases, the carbon rich austenite decomposes into bainite with fine carbide. The finely precipitated carbides can give rise to a high value of hardening rate, and the variation of tensile stress according to the volume fraction of retained austenite is smaller than that of 0.2% yield stress and total elongation[12]. The total elongation for 840 °C is smaller
Table 3. Calculated values of a, b and N of ferrite, bainite and martensite of steels intercritically annealed at 800 °C and isothermally transformed at 450 °C

<table>
<thead>
<tr>
<th>Phase</th>
<th>Holding time at 450°C</th>
<th>a (MPa)</th>
<th>b</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite</td>
<td>1 min</td>
<td>887</td>
<td>0.002</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>10 min</td>
<td>889</td>
<td>0.002</td>
<td>0.11</td>
</tr>
<tr>
<td>Bainite</td>
<td>1 min</td>
<td>967</td>
<td>0.0005</td>
<td>0.149</td>
</tr>
<tr>
<td></td>
<td>10 min</td>
<td>1255</td>
<td>0.0005</td>
<td>0.147</td>
</tr>
<tr>
<td>Martensite</td>
<td>1 min</td>
<td>2968</td>
<td>0.1×10^{-6}</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>10 min</td>
<td>2607</td>
<td>0.1×10^{-6}</td>
<td>0.083</td>
</tr>
</tbody>
</table>

Fig. 2. Tensile properties of steels isothermally treated at 450 °C after intercritical annealing at 840 °C and 800 °C for 5 min

than that for 800 °C although the volume fraction of retained austenite for 840 °C is higher than that for 800 °C. It seems to be in closer correlation with the decrease in bainite and increase in ferrite. Bainit forms as the main constituents from the higher intercritical temperature. However, ferrite is mainly formed at the lower intercritical temperature. Ferrite is softer and has a larger ductility than bainite. Besides, ferrite easily accepts the volume expansion of retained austenite accompanied with strain-induced transformation, leading to the better exhibition of the TRIP effect[13].
Fig. 4. The volume fractions and carbon contents of retained austenite of steels

5.2 FEM Analysis

FEM calculations have been carried out to examine the influence of the volume fraction of retained austenite on uniaxial behavior of Si-Mn TRIP steels. To take into account the effect of microstructure on the stress and strain behavior, optical micrographs and TEM images are taken into account to develop the mesh for the FEM analysis. Fig. 5 shows the initial mesh to describe the microstructure shown in Fig. 3. The microstructures were treated as a composite material composed of elliptic bainite, elliptic austenite surrounded by ferrite matrix and the austenite surrounded by bainite. The aspect ratios of bainite and austenite were assumed to be same to that of unit cell. Also, the volume fraction of retained austenite in bainite is assumed to be same to that in ferrite. To remove end effect, stress and strain were measured on unit cell OABC. The calculations were carried out at the plane strain condition.

Fig. 6 (a) and (b) show the measured and calculated stress-strain curves and the volume fraction of martensite-strain curves of intercritically annealed at 800 °C and isothermally transformed steels at 450 °C for 1min and 10 min, respectively. As is seen in Fig. 4, the isothermally transformed steel for 1 min has lower yield stress than the steel for 10 min due to higher volume fraction of retained austenite. As the volume fraction of martensite increases during uniaxial tension, the former has higher tensile stress than the latter. The FEM calculation based on micromechanical model shows that the effect of TRIP phenomenon on the yield stress and tensile stress. The calculated yield stress decreases and tensile stress increases as the volume fraction of retained austenite increases.

6. Conclusion

Stress-strain relationships of Si-Mn TRIP steels have been studied by uniaxial tension experiment and the FEM analysis with micromechanical model. The characterization of microstructure was taken into account by using self-consistent model by Eshelby and unit cell model in FEM analysis. A maximum retained austenite volume fraction was obtained for early stage of isothermal transformation time of 1 min in intercritical annealing temperature 800 °C and 840 °C. As the bainite isothermal transformation time increased, the volume fraction of retained austenite decreased due to formation of bainite. Tensile stress and total elongation decreased, and the 0.2% yield stress increased with decreasing of the volume fraction of retained austenite. Numerical results were in good agreement with experimental data.
Fig. 5. Initial FEM mesh and boundary condition

Fig. 6. Calculated and experimental flow curves and the volume fractions of martensite of the steels intercritically annealed at 800 °C and isothermally transformed at 450 °C
(a) 1 min at 450 °C
(b) 10 min at 450 °C

References
2. A. Zarei Hanzaki and S. Yue, ISIJ Int., 37 (1997), 583
5. G. B. Olson and M. Cohen, Metall. Trans. 6A (1975), 791
6. R. L. Miller, Trans. ASM, 57 (1964), 892
9. ABAQUS version 5.8, Hibbit, Karlsson & Sorensen, Providence, R.I.
12. A. Zarei Hanzaki, P. D. Hodgson and S. Yue, ISIJ Int. 35 (1995), 79
13. Osamu Matsumura, Yasuharu Sakuma and Hiroshi Takechi, ISIJ Int., 27 (1987), 571