Stress-Induced Martensitic Transformation Behaviors at Various Temperatures and Their TRIP Effects in SUS304 Metastable Austenitic Stainless Steel

Noriyuki TSUCHIDA,1) Yoshiki MORIMOTO,2) Tomoyuki TONAN,3) Yuji SHIBATA,4) Kenzo FUKAURA5) and Rintaro UEJI6)  
1) Graduate School of Engineering, University of Hyogo, 2167 Shosha, Himeji 671-2280 Japan.  
2) Formerly Graduate Student, University of Hyogo. Now at Nippon Metal Industry Co., Ltd., 1 Hama-cho, Hekinan 447-8610 Japan.  
3) Formerly Undergraduate Student, University of Hyogo. Now at Kobe Steel Ltd., 2 Nadahama Higashicho, Nada-ku, Kobe 657-0863 Japan.  
4) Formerly Undergraduate Student, University of Hyogo. Now at HI-LEX Corporation, 1-12-28 Sakaemachi, Takarazuka 665-0845 Japan.  
5) Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu 761-0396 Japan.  
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The effect of temperature on the static tensile properties of the metastable austenitic steel JIS-SUS304 was investigated to clarify the conditions of stress-induced martensitic transformation behavior for maximum uniform elongation. Results of the static tensile tests showed that the tensile strength increased with decreasing temperature and that uniform elongation reached a maximum value at 308 K. The inverse temperature dependence of 0.2% proof stress was observed below 243 K. The volume fraction of martensite increased with decreasing deformation temperature. The conditions under which the stress-induced transformation resulted in the maximum uniform elongation due to the transformation-induced plasticity (TRIP) effect in SUS304 steel were summarized in terms of the martensite volume fraction and rate of transformation. The martensite volume fraction at true strain, which indicates the maximum transformation rate, was found to be approximately 35% independent of the deformation temperature. In stress–strain relationships for which the maximum uniform elongation was obtained, both the evolution rate of the dislocation density and the work-hardening continued to increase until near-uniform elongation was observed, and the maximum calculated value of work-hardening was almost 20 MPa/%.  
KEY WORDS: TRIP; stress-induced transformation; uniform elongation; stress–strain curve; metastable austenitic steel.

1. Introduction  
Transformation-induced plasticity (TRIP) is widely known to be a representative strengthening mechanism for steels.1–3) Thus far, the TRIP effect has been investigated for metastable austenitic stainless steels,3–10) 9% Ni steels,11) and TRIP-aided multi-microstructure steels.12–14) In the previous studies, various important factors that influence stress-induced transformations,1,3–7) kinetics of transformations,3,12) and mechanical properties in prediction models for TRIP8,14,15) have been investigated. However, the relationship between the stress-induced martensitic transformation behavior and the improvement in uniform elongation due to the TRIP effect has not been focused upon.  
From the results of experiments on various Fe–Ni–C alloys, Tamura et al.3,4) demonstrated that the following conditions are required to obtain the maximum elongation due to TRIP:  
(i) The austenite phase alone must deform under strains of up to 20% at least in the early stages of deformation.  
(ii) In deformation under large strains of more than 20%, martensitic transformation is momentarily induced by straining.  
Stress-induced martensitic transformation clearly plays an important role in enhancing uniform elongation due to the TRIP effect. Hence, a quantitative discussion of the correlation between stress-induced transformation and uniform elongation is desirable.  
In this study, we focused on the effect of temperature on stress-induced transformation to summarize various transformation behaviors. In the present paper, we aim to clarify the conditions under which stress-induced martensitic transformation results in the maximum uniform elongation due to the TRIP effect; we summarize the temperature dependence of stress-induced transformation behavior and uniform elongation in metastable austenitic stainless steel.

2. Experimental Procedures  
In this study, the commercial metastable austenitic stainless steel JIS-SUS304, with a thickness of 1.5 mm, was
used. The chemical compositions of the steels are listed in Table 1. By employing the equation used by Sanga et al., the Ni equivalent was calculated to be 23.1%. Figure 1 shows an optical micrograph of the SUS304 steel. The average austenite grain size measured by the line intercept method was 23 μm. Tensile test specimens with a gage length of 25 mm and gage width of 5 mm were machined from the sheets. Static tensile tests were performed with an initial strain rate of $3.3 \times 10^{-4}$ s$^{-1}$ at various test temperatures between 123 and 373 K by using a gear-driven type Instron machine. Test samples deformed by various amounts of true strains were also prepared for X-ray diffraction analysis to investigate the effect of temperature on the stress-induced transformation kinetics. Quantitative estimation of the austenite and martensite phases by X-ray diffraction was based on the principle that the total integrated intensity of all diffraction peaks for each phase in a mixture is proportional to the volume fraction of that phase.

3. Results and Discussions

3.1. Effect of Temperature on Mechanical Properties in SUS304 Steel

Figure 2 presents the nominal stress–strain curves for SUS304 steel obtained by static tensile tests at various test temperatures. The mechanical properties are summarized by the test temperature in Fig. 3 and Table 2. The tensile strength increased with decreasing temperature, and the uniform elongation reached its maximum at 308 K. Figure 4 shows the early stage of nominal stress–strain curves at various deformation temperatures. The inverse temperature dependence of 0.2% proof stress was observed below 243 K. This has been associated with the transformation strain of stress-induced martensite formed before yielding of austenite, thus, the $M_s$ temperature for SUS304 steel appears to be approximately 243 K. This has been associated with the transformation strain of stress-induced martensite formed before yielding of austenite. The $M_s$ temperature for SUS304 steel was also obtained by the SS-TV-TT (single specimen temperature variable testing test) technique. Figure 5 shows the true stress and work-hardening rate as functions of true strain at various temperatures. The work-hardening rate depended greatly on the deformation temperature; below room temperature, it stopped decreasing and began to increase again. The work-hardening rate appears to be affected by the stress-induced martensitic transformation behavior. The enhancement of uniform elongation at 308 K was attributed to the suppression of necking because a higher work-hardening rate than flow stress could be maintained until higher strains were reached.

3.2. Temperature Dependence of Stress-induced Martensitic Transformation Behaviors during Tensile Deformation

Figure 6(a) shows the volume fractions of stress-induced martensite as a function of true strain at various temperatures. In this figure, plots are the measured results by X-ray diffraction analysis, and solid or dashed lines are described by the following equation proposed by Matsumura et al.:
where \( V_a \) is the volume fraction of stress-induced martensite, \( V_{g0} \) is the volume fraction of austenite before deformation, \( \varepsilon \) is the true plastic strain, and \( k \) and \( q \) are constants.\(^{12)}\) In Fig. 6(a), the solid lines show the results calculated by Eq. (1) before necking and the dashed lines show those for higher strains. The volume fractions of martensite at the same \( \varepsilon \) increased with decreasing of deformation temperature. Deformation at 373 K resulted in no stress-induced martensite transformation detected by X-ray diffraction, which means the \( M_d \) temperature for SUS304 steel is between 323 and 373 K. The constants \( k \) and \( q \) in Eq. (1) as determined by the curve fitting of experimental results are summarized in Table 3. The value of \( k \) increased and that of \( q \) decreased with decreasing temperature, indicating an increase in the rate of transformation. As shown in Fig. 6(a), Eq. (1) may suffice to describe various stress-induced martensitic transformation behaviors of SUS304 steel. Figure 7(a) represents the volume fraction of martensite at \( \varepsilon = 0.3 \) as a function of deformation temperature in SUS304 steel. Judging from Fig. 7(a), the \( M_{d0} \) temperature in

### Table 2. Mechanical properties obtained by tensile tests at various temperatures with an initial strain rate of \( 3.3 \times 10^{-5} \) s\(^{-1}\).

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>0.2% proof stress (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Uniform elongation (%)</th>
<th>Total elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>260</td>
<td>1455</td>
<td>38.7</td>
<td>45.5</td>
</tr>
<tr>
<td>173</td>
<td>268</td>
<td>1257</td>
<td>42.6</td>
<td>50.9</td>
</tr>
<tr>
<td>223</td>
<td>302</td>
<td>1112</td>
<td>47.0</td>
<td>55.0</td>
</tr>
<tr>
<td>243</td>
<td>325</td>
<td>1040</td>
<td>50.7</td>
<td>57.6</td>
</tr>
<tr>
<td>273</td>
<td>313</td>
<td>954</td>
<td>58.7</td>
<td>64.8</td>
</tr>
<tr>
<td>296</td>
<td>307</td>
<td>790</td>
<td>79.9</td>
<td>83.6</td>
</tr>
<tr>
<td>308</td>
<td>311</td>
<td>786</td>
<td>82.7</td>
<td>85.2</td>
</tr>
<tr>
<td>323</td>
<td>298</td>
<td>696</td>
<td>68.5</td>
<td>74.3</td>
</tr>
<tr>
<td>373</td>
<td>270</td>
<td>585</td>
<td>54.0</td>
<td>64.0</td>
</tr>
</tbody>
</table>
SUS304 steel is approximately 280 K.

3.3. Enhancement of Uniform Elongation by the TRIP Effect in Terms of Stress-induced Martensitic Transformation

This section discusses the conditions for stress-induced martensitic transformation to obtain the maximum uniform elongation by the TRIP effect as demonstrated by the stress-induced transformation behaviors shown in Figs. 6 and 7. The maximum uniform elongation in SUS304 steel was 82.7% at 308 K.

At 308 K, the volume fraction of stress-induced martensite at $\varepsilon=0.3$ was 5.2%, as shown in Fig. 7(a). Figure 7(b) presents the volume fraction of martensite at $\varepsilon=0.3$ in SUS301L and SUS316L steels. In Figs. 7(a) and 7(b), the open plots indicate the results at maximum uniform elongation for each specimen. Although the temperatures at maximum uniform elongation were different for the three steels, the volume fractions of martensite at $\varepsilon=0.3$ for the maximum uniform elongation were approximately 5% independent of the deformation stability for austenite. Therefore, one condition for the maximum uniform elongation due to the TRIP effect is that the volume fraction of stress-induced martensite at $\varepsilon=0.3$ should be approximately 5%.

Figure 6(b) shows the rate of stress-induced transformation per unit strain ($dV'/d\varepsilon$) as a function of $\varepsilon$ at various temperatures. The term $dV'/d\varepsilon$ denotes the slope of the curves in Fig. 6(a) and can be calculated by using Eq. (1) with the constants $k$ and $q$ in Table 3. The value of $dV'/d\varepsilon$ at each temperature increased to the maximum after the start of deformation and decreased after the maximum rate. The maximum rate of stress-induced transformation ($dV'/d\varepsilon)_{\text{max}}$ became high, but $dV'/d\varepsilon$ decreased abruptly with decreasing deformation temperature. The value of ($dV'/d\varepsilon)_{\text{max}}$ at 308 K was almost 2 and the true strain for ($dV'/d\varepsilon)_{\text{max}}$ at 308 K was close to uniform elongation. ($dV'/d\varepsilon)_{\text{max}}$ was also approximately 2 in SUS301L steel, which has a different deformation stability for austenite.

In previous studies, one condition for obtaining maximum uniform elongation was that the martensite should continue to be induced until the latter stage of deformation or the onset of necking. This condition corresponds to the stress-induced transformation behavior at 308 K in the present SUS304 steel. Hence, as a second condition for obtaining the maximum TRIP effect, the rate of stress-induced martensitic transformation per unit strain ($dV'/d\varepsilon$) should achieve its maximum near uniform elongation, and its maximum transformation rate should be approximately 2.

On the other hand, after summarizing the relationship between the volume fraction of martensite and the transformation rate as shown in Figs. 6(a) and 6(b), the volume fraction of stress-induced martensite at ($dV'/d\varepsilon)_{\text{max}}$ was found to be approximately 35% independent of the deformation temperature. It is very interesting that such a correlation between the volume fraction of martensite and the transformation rate can be observed in the effect of temperature on stress-induced martensitic transformation behavior.

Figure 8 shows relationships between the true stress $\sigma$ and work-hardening rate ($d\sigma/d\varepsilon$) and $\varepsilon$ at various temperatures to facilitate discussion on the work-hardening behavior in SUS304 steel. In Fig. 8, $d\sigma/d\varepsilon$ at each temperature was normalized by the temperature-dependent shear modulus $\mu$ of austenite. In previous studies, the work-hardening behavior of some metals and alloys can be understood by the relationships between $d\sigma/d\varepsilon$ and $\sigma$. $d\sigma/d\varepsilon$ and $\sigma$ can be described as functions of the dislocation density by using the following Bailey–Hirsch type equation:

$$\sigma = c_0 b \sqrt{\rho}$$

$$\frac{d\sigma}{d\varepsilon} = \frac{d\sigma}{d\rho} \frac{d\rho}{d\varepsilon} = c_0 b \sqrt{\rho} \frac{d\rho}{d\varepsilon}$$

$$\frac{d\sigma}{d\rho} = c_0 b \sqrt{\rho} \frac{d\rho}{d\varepsilon} = \left(\frac{c_0 b}{2}\right) \frac{d\rho}{d\varepsilon}$$

where $\sigma$ is the flow stress, $\rho$ is the dislocation density, $b$ is
the Berge vector, and $\alpha$ is a constant. According to Eq. (4), $\sigma d\varepsilon / d\varepsilon$ is closely associated with the evolution rate for the dislocation density $d\rho / d\varepsilon$. $d\rho / d\varepsilon$ can usually be determined by the competition between the storage and annihilation of dislocations.\(^{22,23}\) The storage of dislocations is associated with the athermal storage of dislocations, and the annihilation of dislocations is associated with dynamic recovery. $d\sigma / d\varepsilon$ can also be described by using the athermal and dynamic recovery terms as follows\(^{22,24}\):

$$\frac{d\sigma}{d\varepsilon} = \Theta_s - \Theta_d (\varepsilon, T, \sigma) \quad \text{..........................}(5)$$

where $\Theta_s$ is an athermal contribution to $d\sigma / d\varepsilon$ and $\Theta_d$ is the dynamic recovery term, which is influenced by thermal activation as a function of strain rate $\dot{\varepsilon}$, temperature $T$, and $\sigma$.\(^{22,23}\) By combining Eqs. (4) and (5), $\sigma d\sigma / d\varepsilon$ can be described by the following equation:

$$\sigma \frac{d\sigma}{d\varepsilon} = \sigma (\Theta_s - \Theta_d (\varepsilon, T, \sigma)) \quad \text{..........................}(6)$$

As shown in Fig. 8, $(\sigma d\sigma / d\varepsilon)/\mu^2$ at each temperature increased after tensile deformation started and decreased after the maximum. During this time, as the temperature decreased, the initial behaviors described by the straight line became larger and began to decrease at smaller $\varepsilon$. When considering the $(\sigma d\sigma / d\varepsilon)/\mu^2$ behavior in terms of Eqs. (4) and (6), a decrease in $(\sigma d\sigma / d\varepsilon)/\mu^2$ can be attributed to the dynamic recovery. In the $\sigma d\sigma / d\varepsilon$ behavior of some single crystals and polycrystals,\(^{23,24}\) the initial behaviors were well described by a straight line through the origin for all temperatures, which led to the determination of $\Theta_s$. However, the differences in the initial slope for the tested results seem to mainly be due to the effect of temperature on stress-induced transformation. A lower temperature entails a higher volume fraction of stress-induced martensite during tensile deformation. This leads to a higher flow stress for deformation and a higher work-hardening rate. The initial slope of $(\sigma d\sigma / d\varepsilon)/\mu^2$ is therefore enhanced with decreasing deformation temperature. However, because the transformation is saturated at smaller strains, it is difficult to continue work hardening, indicating that dynamic recovery prevails in work-hardening behavior. The effect of dynamic recovery on the stress-strain curve at 308 K was small because $(\sigma d\sigma / d\varepsilon)/\mu^2$ continued to increase up to around uniform elongation.

When examining Figs. 6 and 8(b) carefully, one would find the values of $(\sigma d\sigma / d\varepsilon)/\mu^2$ at $(dV_p / d\varepsilon)_{\text{max}}$ ranged between $3 \times 10^{-2}$ and $3.5 \times 10^{-4}$ for each temperature. Furthermore, this value was almost consistent with the maximum of $(\sigma d\sigma / d\varepsilon)/\mu^2$ at 308 K. By using the values of $(\sigma d\sigma / d\varepsilon)/\mu^2$ at $(dV_p / d\varepsilon)_{\text{max}}$ for each temperature, $d\rho / d\varepsilon$ and the amount of work hardening per unit strain $(\Delta \sigma)$ can be calculated through Eqs. (2) and (4) as follows:

$$\frac{d\rho}{d\varepsilon} \equiv 1.0 \times 10^{14} \text{ (m}^{-2} / \% \text{)} \quad \text{..........................}(7)$$

$$\Delta \sigma = 20 \text{ (MPa/\%)} \quad \text{..........................}(8)$$

$\Delta \sigma$ is also consistent with the maximum work hardening $\Delta \sigma_{\text{max}}$ at 308 K. This summary strongly suggests that $d\rho / d\varepsilon$ and $\Delta \sigma$ continue increasing up to near uniform elongation and that $\Delta \sigma_{\text{max}}$ is almost 20 MPa/\% in the stress–strain relation when maximum uniform elongation is obtained by TRIP in SUS304 steel. If the value of $\Delta \sigma_{\text{max}}$ is more than 20 MPa/\%, the tensile strength becomes larger, but the uniform elongation is smaller, which is similar to the results for lower temperatures. When the value of $\Delta \sigma_{\text{max}}$ is less than 20 MPa/\%, both the tensile strength and uniform elongation appear to be smaller than those at 308 K because of the kinetics of transformation at 323 K. Because Eq. (8) was obtained by the experimental results of SUS304 steel, $\Delta \sigma_{\text{max}}$ can be expected to be dependent on the chemical compositions of specimens.

4. Conclusions

In this study, the effect of temperature on the mechanical properties and stress-induced martensitic transformation behaviors in JIS-SUS304 steel was investigated to clarify the conditions for realizing maximum uniform elongation due to the TRIP effect. The following conclusions can be obtained from this study.

1. In the static tensile tests at temperatures between 123 and 373 K, the tensile strength increased with decreasing temperature, and uniform elongation reached a maximum at 308 K. The inverse temperature dependence for 0.2% proof stress was observed below 243 K.

2. In the stress-induced transformation behavior measured by X-ray diffraction analysis, the volume fraction of martensite increased with decreasing deformation temperature.

3. The conditions of stress-induced martensitic transformation to realize maximum uniform elongation by the TRIP effect can be summarized in terms of the martensite volume fraction and rate of transformation.

4. The martensite volume fraction at true strain showing the maximum transformation rate was approximately 35% independent of the deformation temperature.

5. In the stress–strain relations for which the maximum uniform elongation was obtained, the evolution rate of the dislocation density and the work hardening continued to increase up to near uniform elongation, and the calculated maximum value of work hardening was almost 20 MPa/\%.

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REFERENCES