Formulation of Static Recrystallization of Austenite in Hot Rolling Process of Steel Plate*

By Atsuhiko YOSHIE,** Hirofumi MORIKAWA,** Yasumitsu ONOE** and Kametaro ITOH***

Synopsis
A critical condition for static recrystallization of austenite (γ) in plate rolling process has been formulated in terms of the change in average dislocation density. The latter was calculated from the decrease in stress due to recovery and recrystallization observed by the double deformation tests. The main results are summarized as follows:
(1) The relation among stress, strain and average dislocation density has been formulated. By the present formulation, deformation stress for practical conditions of the controlled rolling of plate can be calculated as a function of temperature, strain, strain rate and γ grain size.
(2) The behavior of static recovery and recrystallization taking place during holding period after deformation has also been formulated as a function of dislocation density. This formulation makes it possible to estimate the critical condition for static recrystallization during an interval time between the successive rolling passes of plate.
(3) Deformation conditions such as temperature, strain, strain rate, γ grain size and interval time between passes affect the critical condition for recrystallization. The shorter interval time elevates the temperature limit of non recrystallization.

Key words: hot deformation; static recrystallization; austenite; plate rolling; incubation time; mathematical model.

I. Introduction
Controlled rolling process has become one of the important processes in steel plate production. Especially the total reduction in the temperature range of non recrystallization has been increased for improving the mechanical properties. Therefore, it is indispensable for the process design to make clear the critical condition for recrystallization of austenite (γ) in hot rolling.

As seen in the schematic illustration of Fig. 1, the critical condition for static recrystallization of γ is considered to be a function of temperature, stored strain, strain rate in rolling and γ grain size as well as chemical compositions of steels. In higher temperature range, the critical strain (εcr) for recrystallization is smaller than the strain in each pass of commercial plate rolling. As a result, recrystallization starts during the interval time before the next pass. In lower temperature range, however, recrystallization does not begin until an accumulated strain of several passes exceeds εcr, because the strain of each rolling pass does not usually exceed εcr.

The critical conditions for recrystallization have been investigated by many authors. Some authors1-3 have observed the microstructure of steels quenched after hot rolling and shown the maps of rolling conditions which are divided into recrystallization range and non recrystallization range. This method, however, requires the growth of recrystallized grains to observable size to define the onset of recrystallization, so the observed start of recrystallization may be apparent and different from its true start (i.e., nucleation). Moreover, when a lower hardenability steel is employed or a specimen is heavily deformed, it is difficult to discern prior γ grain structure because quenched γ transforms to martensite insufficiently. For these reasons, the critical condition derived from microstructural observation might not be accurate. Other authors4,5 have performed the double deformation tests and reported an empirical criterion of recrystallization: a value of softening ratio specified at the inflection in a softening ratio vs. time curve. However, the physical meaning of the specific value of softening ratio in this method is indefinite. Recently some authors6-8 have formulated mathematically the behavior of recrystallization in hot rolling process in terms of the changes in observed microstructure. The critical condition for static recrystallization, however, was not described quantitatively, because the

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incubation period of recrystallization was not taken into account in their calculation.

In the present report the critical condition for recrystallization in hot rolling process has been expressed in a mathematical model by taking the incubation period into consideration. The model has been derived not from the change in observed microstructure but from the decrease in the stress observed in the present double deformation tests. In order to estimate the critical condition, the observed stress has been related to the average dislocation density ($\rho$) because the relations among $\rho$, strain and stress have been clarified by many authors.7,9,10

II. Mathematical Model

1. Procedure of Mathematical Analysis

Figures 2(a) and 2(b) shows a schematic illustration of the changes in average dislocation density and stress-strain curves in double deformation tests.11) Average dislocation density increases with deformation and decreases during interval time due to the progress of recovery and recrystallization. On the assumption that stress ($\sigma$) corresponds to $\rho$, the value of $\rho$ at each point (for example, point A or B in Fig. 2(a)) can be calculated from the observed $\sigma$ (for example, stress-strain curves A or B in Fig. 2(b)).

Senuma et al.12) formulated deformation resistance of hot strip steel as a function of $\rho$. At the 1st step of the present analysis, the relation between $\sigma$ and $\rho$ is formulated in the same way. At the 2nd step, the decrease in $\rho$ due to recovery and recrystallization is formulated as a function of time after deformation including undetermined coefficients. At the 3rd step, the values of undetermined coefficients are determined from the decrease in $\rho$ during interval time calculated through the observed $\sigma$ in double deformation tests. With these procedures, progress of recovery and recrystallization after deformation is formulated mathematically. The schematic illustration of the procedures of analysis is also shown in Fig. 2.

2. Relation among Deformation Stress, Strain and Average Dislocation Density

Deformation stress during hot working is expressed as

$$\sigma = \sigma_{id} + \sigma_{e},$$ ................................(1)

where $\sigma_{id}$ is an internal stress and $\sigma_{e}$ is an effective stress. As the latter term can be neglected when $\sigma$ is deformed at high temperature,9) the relation between $\sigma$ and $\rho$ is expressed as

$$\sigma \approx \sigma_{id} = a\rho^{1/2},$$ ........................(2)

where $a$ is a constant.

Next, the relation between strain ($\varepsilon$) and $\rho$ will be derived. Strain hardening and dynamic recovery proceed simultaneously with hot deformation. The change in $\rho$ is formulated into the following differential equation.

$$d\rho = (\partial \rho/\partial \varepsilon)d\varepsilon + (\partial \rho/\partial t)dt$$ ................................(3)

As the rolling strain of plate is relatively small, $\rho$ is assumed to be proportional to $\varepsilon$.13) Therefore the rate of strain hardening $(\partial \rho/\partial \varepsilon)$ is expressed as

$$\partial \rho/\partial \varepsilon = b$$ .......................................(4)

where $b$ is a function of temperature ($T$)9) and

$$b = b_0 \exp (Q_b/RT)$$ ....................................(5)

where $b_0$: a constant, $Q_b$: an apparent activation energy and $R$: the gas constant (8.314 J·mol$^{-1}$·K$^{-1}$). Dislocation configuration corresponds to $\varepsilon$ and multiplication of dislocation depends on $T$. The effect of strain rate ($\dot{\varepsilon}$) and $\gamma$ grain size ($D_\gamma$) are neglected because their contributions are assumed to be small. The rate of dynamic recovery is expressed as

$$\partial \rho/\partial t = -\varepsilon_0^\gamma,$$ ......................................(6)

where $\varepsilon_0$ is a function of $T$, $\dot{\varepsilon}$ and $D_\gamma$. 

![Schematic illustration of the change in average dislocation density (a) and stress-strain curves (b) derived from double deformation test](image-url)
where $\epsilon$, $m$, and $n$ are constants, and $Q_e$ an apparent activation energy. The effect of $D_e$ and $z$ is assumed to be expressed in the form of power function because their dependence on $\epsilon$ is not clear. On the same assumption, the similar functional forms are adopted in Eqs. (10), (14) and (15), which will be discussed below.

The opportunity for annihilation of dislocations with opposite Burgers-vector (n=2 in Eq. (6)) is very few because dislocations hardly cross-slip in f.c.c. crystal. Therefore dislocation can annihilate mainly due to climbing and absorption at grain boundary (n=1 in Eq. (6)). With the combination of Eqs. (4) and (6) with n=1, the relation between $\rho$ and $\epsilon$ is formulated for a constant $t$ through the deformation as

$$
\frac{\partial \rho}{\partial t} = -d \cdot \rho,
$$

where $\rho_0$ is the dislocation density of annealed steel. From Eqs. (2) and (8), stress-strain relations of any deformation conditions of the controlled rolling of plate in $\tau$ temperature range can be calculated.

3. Relation between Static Recovery and Average Dislocation Density

The annihilation rate of $\rho$ during static recovery after deformation is expressed in the same form as that of dynamic recovery as

$$
\frac{\partial \rho}{\partial t} = -d \cdot \rho,
$$

where $t$ is time after deformation and

$$
d = d_0 D_T^{m_2 n_2 e} \exp \left( \frac{Q_e}{RT} \right),
$$

where $d_0$, $m_2$, $n_2$ and $Q_e$ are constants, and $Q_e$ an apparent activation energy. When $\rho = \rho_A$ at $t = 0$ and $\rho = \rho_0$ at $t = \infty$, the relation between $\rho$ and $t$ is formulated into

$$
\rho = (\rho_A - \rho_0) \exp \left( -d \cdot t \right) + \rho_0,
$$

where $\rho_A$ is a dislocation density just after hot deformation.

4. Relation between Static Recrystallization and Average Dislocation Density

After static recrystallization starts at $t = \tau$ ($\tau$: incubation period), $\rho$ decreases according to Eq. (12) due to progress of recrystallization and becomes $\rho_0$ after recrystallization completes.

$$
\rho = (\rho_0 - \rho_e) X + \rho_e,
$$

where $X$ is the fraction recrystallized, and $\rho_e$ is the dislocation density according to Eq. (11). The value of $X$ is expressed as a function of $t$ into the following equation:

$$
X = 1 - \exp \left[ -\epsilon(t - \tau)^{\gamma} \right],
$$

where $\epsilon$ is a function of $T$, $\gamma$, $D_T$ and $\rho_e$ as in the form of

$$
\epsilon = \epsilon_0 D_T^{m_0 n_0 e} e^{\gamma} \exp \left( \frac{Q_e}{RT} \right),
$$

where $\epsilon_0$, $m_0$, $n_0$ and $l_\gamma$ are constants, and $Q_e$ an apparent activation energy. Incubation period, $\tau$, is a function of $T$, $\gamma$, $\epsilon$ and $D_T$, as

$$
\tau = \tau_0 D_T^{m_\gamma n_\gamma e^{\gamma}} \exp \left( \frac{Q_e}{RT} \right),
$$

where $\tau_0$, $m_\gamma$, $n_\gamma$, and $l_\gamma$ are constants, and $Q_e$ an apparent activation energy. The value of $n$ in Eq. (13) is assumed to be a constant value of 2, on the basis of the present experimental data and the report of other authors.

By substitution of Eq. (13) into Eq. (12), the relation among $\rho$, $\epsilon$, $t$ and $\tau$ is obtained. By expanding the term of $t$ and $\tau$ into series and neglecting the terms of higher order after twice logarithmic calculation, it is possible to obtain a linear equation of $\rho$, $\epsilon$, $t$ and $\tau$. The values of $\epsilon$ and $\tau$ are determined by regression analysis with the series of $\rho$ calculated from the observed stress at $\epsilon = 0.05$ ($\sigma_{o.05}$) in the 2nd pass of double deformation tests in which $T$, $\epsilon$, $\gamma$ and $D_T$ are constant and $t$ as a variable. The constants included in Eqs. (14) and (15) are also obtained by regression analysis with the calculated $\epsilon$ and $\tau$ for different $T$, $\epsilon$, $\gamma$ and $D_T$.

With the combination of the equations mentioned above, static recovery and recrystallization behavior and the critical condition of recrystallization can be calculated. This mathematical model can be applied to multi-pass rolling, because $\rho$ can be calculated consistently from the beginning to the end of rolling process.

III. Materials and Experimental Methods

The chemical composition of steels used are shown in Table 1. The high hardenability steel A containing Ni, Mo and B was employed for the comparison between microstructure and deformation stress and Nb steel B was employed for this formulation which was a typical steel for plates produced by controlled rolling. Single or multi deformation tests were performed by using a compression type hot deformation simulator. Specimens were machined from continuous casting slabs to the column with a size of 7 mm diameter and 12 mm height.

The specimens were heated in an induction furnace to the heating temperature (HT) at a heating rate of $5^\circ C/s$, and held for 10 min followed by cooling to each deformation temperature (DT) at a cooling rate of $5^\circ C/s$. The fluctuation of temperature in the specimen is proved to be within $5^\circ C$ during heating and cooling and within $2^\circ C$ during holding. Then single or multi axial compressions were performed at DT immediately. Strain, deformation speed, interval time during deformation and temperature were precisely controlled through a computer. In the case of double deformation test, stress-strain curves of the 2nd pass were measured just after holding time ranging 1~1 000 s after the 1st pass. The prior $\gamma$ grain boundaries were observed in some specimens quenched just after the same holding time.
1. Comparison between Microstructure and Deformation Stress

Steel A was employed for the observation of the prior γ grain boundaries of a quenched specimen after deformation. Figures 3 and 4 are the optical microstructures of the quenched specimens and the observed stress-strain curves, respectively. These figures show the decrease in deformation stress in the 2nd pass due to the progress of recrystallization. Figure 5 shows the relation among the time after the 1st pass, the fraction of γ recrystallized, X, and $\sigma_{\gamma-0.05}$ of the 2nd pass. The value of X was measured from the micrographs. Figure 5 reveals that the decrease in $\sigma$ for $t < 10$ s is caused by recovery and that for $t \geq 10$ s by recovery and recrystallization. From these data, however, it is impossible to determine exactly the true start of recrystallization as mentioned before.

2. Formulation of Recovery and Recrystallization Behavior of 0.01 % Nb Steel

Steel B was employed for this formulation. Table 2 shows the experimental conditions used. Chemical analysis of the specimens quenched just after holding for 10 min at the heating temperature ranging 950~1 200°C confirmed that Nb was completely dissolved even at HT=950°C. Therefore HT is considered to affect $\sigma$ only through $D_\gamma$. In this experiment, $D_\gamma$ varied from 12.5 to 300 μm according to HT from 950 to 1 200°C. The possible effect of Nb precipitation on $\sigma_{\gamma-0.05}$ by holding at a certain temperature before deformation was also investigated. Its effect, however, was very small because both C and Nb contents were relatively small in the steel B. Therefore precipitation hardening can be neglected and only strain hardening is caused by retardation of recovery and recrystallization through the variation of $\sigma$ with Nb.

The constants included in Eqs. (2), (5) and (7) were obtained by regression analysis mentioned before. The units of observed data are kg/mm² for $\sigma$ and μm for $D_\gamma$. Table 3 shows the values of constants. The effect of $D_\gamma$, $m_\gamma$ and $\varepsilon$, $n_\gamma$ on the rate of dynamic recovery are relatively small. The dependence of DT on deformation resistance which is usually

<table>
<thead>
<tr>
<th>Steel</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>Nb</th>
<th>B</th>
<th>N</th>
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<tr>
<td>A</td>
<td>0.12</td>
<td>0.26</td>
<td>1.00</td>
<td>0.014</td>
<td>0.004</td>
<td>0.17</td>
<td>0.91</td>
<td>0.57</td>
<td>0.41</td>
<td>0.071</td>
<td>—</td>
<td>0.001</td>
<td>0.0045</td>
</tr>
<tr>
<td>B</td>
<td>0.07</td>
<td>0.23</td>
<td>1.33</td>
<td>0.016</td>
<td>0.004</td>
<td>0.46</td>
<td>0.79</td>
<td>—</td>
<td>—</td>
<td>0.037</td>
<td>0.01</td>
<td>—</td>
<td>0.0056</td>
</tr>
</tbody>
</table>

Table 1. Chemical compositions of the steels. (wt%)
expressed as Misaka’s type equation\(^9\) is divided into the dependence of strain hardening, \(Q_b\) and that of dynamic recovery, \(Q_e\). As these values are of the same order of magnitude but of the opposite sign, \(\gamma\) increases with decrease in \(\Delta T\). The values of constants included in Eqs. (10), (14) and (15) are also shown in Table 3. The effect of \(D_r\), \(m_e\) and \(\dot{\varepsilon}\), \(n_e\) are also small on the progress of static recovery. The effect of \(\varepsilon\), \(l_\tau\) on the progress of recrystallization is by far larger than that of \(D_r\) and \(\dot{\varepsilon}\). The value of \(l_\tau\) is close to that of experimental formula by the other author.\(^{20}\)

3. Comparison between Experimental Data and Calculated Results

Figure 6 shows the stress–strain curves of various deformation conditions. Calculated results by using Eqs. (2)–(8) are in good agreement with the experimental data in every case. Figure 7 illustrates the decrease in \(\sigma_{\text{exp}}, 0.05\) at the 2nd pass due to the progress of recovery after deformation. Calculation was performed on assumption that only recovery progressed. Experimental data are consistent with the calculated results before the start of recrystallization and deviate with the progress of recrystallization. In the lower \(\Delta T\), Fig. 7(a), the incubation period for recrystallization is considered to be between 20 and 100 s for \(\varepsilon=0.2\) and between 10 and 20 s for \(\varepsilon=0.4\). In the higher \(\Delta T\), Fig. 7(b), recrystallization starts in much shorter period after deformation. Figure 7 reveals that the larger \(\varepsilon\) and the higher \(\Delta T\) result in the shorter incubation period.

Figure 8 shows the decrease in \(\sigma_{\text{exp}}, 0.05\) due to recovery and recrystallization during holding time after deformation. The progress of both recovery and recrystallization were calculated in this case. Lines and solid triangles represent calculated results from Eqs. (11), (12) and (15). Good agreement between experimental data (open marks) and calculated results proves that this mathematical model is effective to estimate the recovery and recrystallization behavior in plate rolling process.

V. Discussion

1. Effect of Nb on Deformation Stress

The decrease in observed stress between the 1st and the 2nd pass arises from the difference between softening due to recovery and recrystallization and precipitation hardening of Nb. Their contribution

<table>
<thead>
<tr>
<th>Eq.</th>
<th>Coefficients</th>
<th>Constants</th>
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<th>Coefficients</th>
<th>Constants</th>
<th>Eq.</th>
<th>Coefficients</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2)</td>
<td>(a)</td>
<td>(1.68 \times 10^{-4})</td>
<td>(10)</td>
<td>(d_p)</td>
<td>(8.78 \times 10^7)</td>
<td>(14)</td>
<td>(m_e)</td>
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</tr>
<tr>
<td>(5)</td>
<td>(b_q)</td>
<td>(1.00 \times 10^9)</td>
<td>(10)</td>
<td>(Q_d)</td>
<td>(-201000)</td>
<td>(14)</td>
<td>(n_e)</td>
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</tr>
<tr>
<td>(5)</td>
<td>(Q_b)</td>
<td>41300</td>
<td>(10)</td>
<td>(m_e)</td>
<td>(-0.134)</td>
<td>(15)</td>
<td>(\tau_0)</td>
<td>(1.40 \times 10^{-12})</td>
</tr>
<tr>
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<td>(10)</td>
<td>(n_e)</td>
<td>0.0772</td>
<td>(15)</td>
<td>(Q_e)</td>
<td>241000</td>
</tr>
<tr>
<td>(7)</td>
<td>(q_e)</td>
<td>217000</td>
<td>(14)</td>
<td>(\varepsilon)</td>
<td>(2.80 \times 10^{10})</td>
<td>(15)</td>
<td>(l_\tau)</td>
<td>(-2.09)</td>
</tr>
<tr>
<td>(7)</td>
<td>(m_e)</td>
<td>0.0412</td>
<td>(14)</td>
<td>(Q_e)</td>
<td>(-432000)</td>
<td>(15)</td>
<td>(m_r)</td>
<td>0.227</td>
</tr>
<tr>
<td>(7)</td>
<td>(n_e)</td>
<td>(-0.0986)</td>
<td>(14)</td>
<td>(l_\tau)</td>
<td>4.29</td>
<td>(15)</td>
<td>(n_e)</td>
<td>0.159</td>
</tr>
</tbody>
</table>

Steel B

Fig. 6. Effect of HT, \(\Delta T\), and \(\dot{\varepsilon}\) on stress–strain curves.

Steel B

Fig. 7. Decrease in deformation stress in the 2nd pass due to recovery of \(\gamma\).

Steel B

Fig. 8. Decrease in deformation stress in the 2nd pass due to recovery and recrystallization.
can not be discerned because of their interactions. Figure 9 shows the effect of Nb content on \( \sigma_{\text{e},0.05} \) obtained by the single deformation test of 0.10%C–1.00%Mn steel. The stresses of specimens held for 500 s at 800°C for precipitation before the deformation were nearly equal to the stresses of the specimens without holding. From Fig. 9, stress increment is proportional to the Nb content in accordance with solution hardening. As the present specimen contains only 0.01% Nb, the precipitation hardening is expected to be no more than 1 kg/mm², which is within the error of observed stress.

Precipitation behavior of Nb(CN) may differ before and after deformation. In this respect, DeArdo et al. reported that Nb(CN) selectively precipitates at grain boundary and subgrain boundary of γ. Therefore the effect of these precipitates on deformation stress might be negligibly smaller than that of coherently precipitated Nb(CN) in matrix. Though the precipitation hardening of Nb(CN) is neglected in the present model, experimental data are consistent with the results of calculations.

2. Critical Condition of Recrystallization after Deformation

Incubation period, \( \tau \), is calculated as a function of \( \varepsilon, T, \dot{\varepsilon} \) and \( D_r \) in Eq. (15). As a result, effect of deformation conditions on the critical conditions for recrystallization can be analyzed by Eq. (15). Figure 10 shows the effect of \( \varepsilon \) on \( \tau \). In the multi-stage deformation test, \( \varepsilon \) in the abscissa is the stored strain calculated with Eq. (8). Calculated results indicate that the higher DT and the smaller \( D_r \) result in the shorter incubation period. Figure 11 shows the critical conditions for static recrystallization of γ. The right upper sides of the lines are the recrystallization ranges and the left lower sides are the non-recrystallization ranges. If an interval time between deformation is longer than the incubation period (parameter in Fig. 11), recrystallization starts during the interval time. Therefore a short interval time elevates the temperature limit of non-recrystallization. Figure 12 shows the relation between applied deformation strain and stored strain at the start of recrystallization. The difference between these strains indicates the decrease in dislocation density due to recovery during the incubation period. Figure 13 shows the effect of \( \varepsilon \) on the softening ratio (S) in double deformation test just at the start of recrystallization. The ratio S is described as

\[
S = \frac{(\sigma_{\text{m}} - \sigma_\text{n})}{(\sigma_{\text{m}} - \sigma_\text{y})}, \quad \text{.........(16)}
\]

where \( \sigma_{\text{m}} \) is the peak stress in the 1st pass, and \( \sigma_\text{n} \) and \( \sigma_\text{y} \) are the yield stress of the 1st and 2nd passes, respectively. These stresses are calculated from Eqs. (2), (8), (11) and (15). In the calculation, \( \sigma_\text{n} \) and \( \sigma_\text{y} \) were taken as \( \sigma_{\text{e},0.05} \) for the 1st and 2nd passes, respectively. Djaic and Jonas, and Ouchi et al. reported that static recrystallization started at a specific value of S, 0.20–0.30. As the strain at the 1st pass were 0.14 or 0.20 respectively in their experiments, the values of S calculated by the present model are nearly 0.2–0.3. From Fig. 13, however, the value of S changes widely with the variation of deformation conditions. A general criterion of recrystallization...
Stabilization is not necessarily described in terms of a specific value of \( S \). On the other hand, the present model predicts satisfactorily the critical condition of recrystallization for comprehensive conditions of hot rolling of plate.

VI. Conclusion

The critical condition of static recrystallization of \( \gamma \) in plate rolling process has been formulated in terms of the change in average dislocation density calculated from the decrease in deformation stress due to recovery and recrystallization in the double deformation tests. The results are summarized as follows:

1. The relation among stress, strain and average dislocation density and the change in dislocation density due to strain hardening and dynamic recovery during deformation have been formulated. By the present formulation, the deformation stress for practical deformation conditions of controlled rolling can be calculated as a function of temperature, strain, strain rate and \( \gamma \) grain size.

2. The behavior of static recovery and recrystallization during holding period after deformation has also been formulated as a function of dislocation density. This formulation successfully predicts the critical condition of recrystallization during the interval time between the successive rolling passes of plate.

3. Deformation conditions such as temperature, strain rate, \( \gamma \) grain size and interval time between passes affect the critical condition of recrystallization. A smaller interval time elevates the temperature limit of non recrystallization.

4. An empirical criterion for the start of recrystallization such as a specific value of softening ratio is not always valid, because the softening ratio changes largely with deformation conditions.

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