Design method for TRIP-aided multiphase steel based on a microstructure-based modelling for transformation-induced plasticity and mechanically induced martensitic transformation

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\textbf{A B S T R A C T}

In recent years, for automotive applications, the need for new advanced high-strength sheet steels (AHSSs) with high ductility has rapidly increased. This is mainly related to the need for more fuel-efficient (and therefore more environmentally friendly) cars, and the increasing consumer demand for safer vehicles. In this research, the transformation-induced plasticity (TRIP) that accompanies the mechanically induced martensitic transformation (MIMT) in TRIP-aided multiphase steel was analyzed. The analysis was performed using a computational model that takes the ductile fracture during tensile deformation into account. The TRIP and MIMT phenomena were calculated using the concept of variant selection, which is based on the Kurdjumov–Sachs (K–S) orientation relationship. To consider the localization of the plastic flow in the deforming material, the increase in void nucleation due to the martensitic transformation and the void growth based on the yield criterion for porous material were studied. The feasibility of the extra advanced high-strength sheet steel (X-AHSS) was assessed by analyzing the results obtained using various initial volume fractions and various stabilities of the retained austenite in the TRIP-aided multiphase steel. Subsequently, the optimum volume fraction and stability of the retained austenite in the TRIP-aided multiphase steel could be determined.

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\section{Introduction}

Many industrial applications requiring high-structural performance and good component formability need both high ductility and strength. As these two material properties are generally antagonistic, it is very difficult to improve them both simultaneously. In recent years, particularly for automotive applications, the desire for new advanced high-strength sheet steels (AHSSs) with high ductility has rapidly increased. This is not only due to the need for lightweight materials, which improve fuel efficiency and therefore reduce environmental pollution, but also the consumer’s increasing demand for safer and more comfortable vehicles.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Map for the combination of tensile strength and elongation as an engineering measure for various sheet steels\cite{1,2,3}.}
\end{figure}

Conventional AHSSs, including dual phase (DP), transformation-induced plasticity (TRIP), complex-phase (CP), martensite (MART), and hot press forming (HPF) steels, are located in between the values of about 10,000 and 25,000 MPa% of the strength–ductility balance, which is the multiplication of the tensile strength and elongation at the engineering measure. Ultra advanced high strength sheet steel (U-AHSS) can be referred to as twinning-induced plasticity (TWIP) steel\cite{1,2,3}. This steel lies at about 60,000 MPa% of the strength–ductility balance in the map shown in Fig. 1. Recently, there has been a dramatically increased interest in the development of a new generation of AHSS, defined as extra advanced high-strength sheet steel (X-AHSS) and shown in Fig. 1\cite{1,2,3}. The TRIP-aided multiphase steel containing a large volume fraction of metastable austenite is one of the most promising types of X-AHSS.

In this research, a microstructure-based computational model, previously suggested for the study of pure metastable austenitic steel\cite{4,5}, has been extended and used to analyze the deformation and phase transformation behavior of the TRIP-aided multiphase steel during tensile testing. To consider the localization of the plastic flow in the deforming material, the increase in void nucleation due to the martensitic transformation and the void growth based on the yield criterion for porous material\cite{6,7,8,9,10,11} were studied. The plastic instability condition for the onset of necking was...
taken as the maximum-load criterion during the uniaxial tensile test. In the proposed model, the TRIP strain was evaluated by assessing the difference in the nucleation rate of each martensitic variant using a method based on the Kurdjumov–Sachs (K–S) orientation relationship [4,5,11,12]. The feasibility of the X-AHSS was assessed by analyzing the results obtained using various initial volume fractions and various stabilities of the retained austenite in the TRIP-aided multiphase steel. Subsequently, the optimum initial volume fraction and stability of the retained austenite in the TRIP-aided multiphase steel, which is corresponding to the appropriate value of the strength–ductility balance in the map of Fig. 1, could be designed.

2. Model for TRIP and MIMT

On the basis of the fact that the martensitic transformation is a nucleation-controlled phenomenon, authors derived a general kinetic model in the metastable austenitic steel for the mechanically induced martensitic transformation (MIMT) including the athermal martensitic transformation kinetics [5]. The probability of nucleation occurring at a given site could be derived for each variant as a function of the interaction energy between the externally applied stress state and the lattice deformation based on the Kurdjumov–Sachs (K–S) relationship. Authors [5] obtained the following expression for the increment of the extended martensite volume fraction in the retained austenite, \( df_{ex} \):

\[
df_{ex} = A'\varepsilon_{pl}^2 + Bd(\Delta G + U')H - d(\Delta G + U')H[(\Delta G - \Delta G - U')]\]

(1)

where \( \varepsilon_{pl} \) is the effective plastic strain increment accumulated in the parent austenite, \( \Delta G \) and \( \Delta G' \) are the chemical free energy change and the critical one at \( M_s \) temperature for the austenite-to-martensite transformation, respectively. \( H \) is the Heaviside step function, reflecting the fact that the martensitic transformation can occur when the driving force exceeds the critical free energy. The mechanical interaction energy, \( U' \), for the \( i \)th variant between the applied stress, \( \sigma \), and the lattice deformation in austenite during phase transformation can be defined by

\[
U' = m_i \sigma_{ij} \varepsilon_{ij}^{S_i}
\]

(2)

where \( \varepsilon_{ij}^{S_i} \) is the transformation strain for \( i \)th martensitic variant on the specimen coordinate, which could be calculated by the tensor transformation rule linking the crystal coordinate and the specimen coordinate, \( m_i \) is the molar volume of the material. It is known that Bain distortion on the crystal coordinate among the lattice deformation has one compressive axis and two tensile axes for the martensitic transformation [4]. To analyze more precisely the lattice deformation (TRIP strain) in the martensitic transformation, the invariant plane strain (IPS) together with the Bain distortion was considered based on the crystallographic theory suggested by Wechsler et al. [13], K–S orientation relationship was assumed for this lattice deformation [14].

The functions of \( A' \) and \( B \) are expressed by the following formula [5]:

\[
A' = \frac{0.011\alpha \delta (f_{sb})^{-1} (1 - f_{sb})}{24 \Delta S}
\]

\[
B = \frac{0.011(1 + \delta (f_{sb})^{-1})}{24 \Delta S}
\]

(3)

where \( \alpha \) is the shear band formation rate, and \( \delta \) and \( r \) are the geometric constants. \( f_{sb} \) is the volume fraction of shear bands. Above equations were derived on the basis of the observation that the strain-induced nucleation occurs predominantly at shear-band intersections [15,16]. \( \Delta S \) is the entropy change (that is, \( \partial \Delta S/\partial T \)) for austenite-to-martensite transformation.

Based on the extension of the classical JMAK (Johnson–Mehl–Avrami–Kolmogrov) theory for the simultaneous decomposition of austenite [17], the real volume fraction of \( i \)th martensitic variant at time, \( t + dt \), is

\[
f_{i,t+dt} = f_i + df_i, \quad df_i = \left(1 - \sum_{i=1}^{24} f_i \right) df_{ex}
\]

(4)

The total volume fraction of martensite in the retained austenite then becomes

\[
f = \sum_{i=1}^{24} f_i
\]

(5)

where \( f \) refers to the volume fraction of the martensite transformed from one parent austenite. Finally, the total volume fraction of martensite, \( X_m \), in the TRIP-aided multiphase steel specimen can be obtained as

\[
X_m = X_{m1} f
\]

(6)

where \( X_{m1} \) is the initial volume fraction of retained austenite in the TRIP-aided multiphase steel.

The transformation strain on the specimen coordinate, \( \varepsilon_{ij}^{S_i} \), was derived on the premise that single grain of austenite was fully transformed to \( i \)th martensitic variant. Considering the rate of increase in the volume fraction of \( i \)th martensitic variant, \( f_i \), the transformation strain rate for \( i \)th martensitic variant at a given time could be defined as follows:

\[
\dot{\varepsilon}_{ij}^{S_i} = f_i \varepsilon_{ij}^{S_i}
\]

(7)

Under the applied stress, the variant selectivity of each variant is related to the nucleation rate of the variant. In one austenite parent grain, the ratio of volume fractions between the 24 variants can be determined by the ratio of nucleation rates between them. Then, the variant selectivity \( S' \) of the \( i \)th variant at a given time can be defined as

\[
S' = \frac{f_i}{\sum_{j=1}^{24} f_j}
\]

(8)
For single grain of parent austenite at a given time, the variant selectivity means the ratio between the increasing rates of volume fraction of each martensitic variant. For the condition of zero applied stress, the interaction energy of the each variant becomes zero. Then, all selectivity for the 24 variants will become the same value of 1/24. Using the concept of the variant selectivity, the transformation strain rate in single grain of parent austenite, $\dot{\varepsilon}_{ij}^{TP}$, can be given by

$$\dot{\varepsilon}_{ij}^{TP} = \sum_{j=1}^{24} S_i^j S_j^i \dot{\varepsilon}_{ij}^{TP}$$  \hspace{1cm} (9)

The above equation can be extended to a polycrystalline TRIP-aided multiphase steel. The overall transformation strain rate on the specimen coordinate at a given time can be evaluated by the arithmetic average of the transformation strain rates for all parent austenite grains, assuming that each austenite grain has the same volume and the iso-stress condition in the austenite grains is valid.

$$\dot{\varepsilon}_{ij}^{TP(T)} = \frac{1}{N} \sum_{j=1}^{N} \dot{\varepsilon}_{ij}^{TP(T)}$$  \hspace{1cm} (10)

where $\dot{\varepsilon}_{ij}^{TP(T)}$ is the overall transformation strain rate of the TRIP-aided multiphase steel specimen containing initially N austenite grains.

3. Constitutive equations

The stress increment of the Cauchy stress ($d\sigma$) is

$$d\sigma = C^e : d\varepsilon^e$$  \hspace{1cm} (11)

where $C^e$ and $d\varepsilon^e$ are elasticity tensor and elastic strain increment, respectively. The total strain increment is

$$d\varepsilon^T = d\varepsilon^e + d\varepsilon^{TP(T)} + d\varepsilon^p$$  \hspace{1cm} (12)

where $d\varepsilon^{TP(T)}$ and $d\varepsilon^p$ are TRIP strain increment associated with the phase transformation and plastic strain increment, respectively. The TRIP strain increment was calculated from the model for the TRIP described in the previous section. The constitutive equation for the plastic strain of a multiphase material, which consists of ferrite, bainite, austenite and martensite was established in a manner similar to that described by Stringfellow et al. [18], applying Eshelby's solution for the isotropic spherical inclusions [19]. Therefore, the stress increment becomes

$$d\sigma = C^e : (d\varepsilon^T - d\varepsilon^{TP(T)} - d\varepsilon^p)$$  \hspace{1cm} (13)

4. Damage analysis

The evolution of the ductile damage and subsequent fracture of the TRIP-aided multiphase steel were analyzed using the Gurson–Tvergaard yield criterion and a void nucleation model based on not only cracking in intrinsically inhomogenous regions such as second-phase particles, but also on decohesion at the austenite–martensite interface [20,21], the area of which is increased due to the MIMT. The overall stress potential, $\phi$, of an isotropic elasto–plastic solid containing a volume fraction, $f_v$, of voids can be written as follows [6,7]:

$$\phi = \left(\frac{\sigma_e}{\sigma_y}\right)^2 + 4q_1f_v\cosh\left(\frac{2}{3}q_2\frac{\sigma_m}{\sigma_y}\right) - (1 + q_4f_v)^2 = 0$$  \hspace{1cm} (14)

where $\sigma_e$, $\sigma_m$ and $\sigma_y$ are the equivalent stress, the mean stress, and the equivalent yield stress of the non-voided solid matrix, respectively. Parameters $q_1$ and $q_2$ are chosen as 1. The evolution law for the void volume fraction due to void growth is determined by requiring the matrix material to be plastically incompressible.

$$\dot{f}_v^{\text{growth}} = (1 - f_v)f_{kk}^p$$  \hspace{1cm} (15)

where $f_{kk}^p$ is the trace of the macroscopic plastic strain rate tensor. The nucleation of voids is known to be a very complex physical process which depends on the microstructure of the material. The microstructural change in TRIP-aided multiphase steel continues during the MIMT. To calculate the increment of the void volume fraction in TRIP-aided multiphase steel due to void nucleation, we adopt the concept of the plastic strain controlled void nucleation model suggested based on the experimental data in Gurland [22]. Since the decohesion at the austenite–martensite interface [5,20,21], the area of which is increased due to the MIMT, may be the major cause of the void nucleation of TRIP-aided multiphase steel, the nucleation rate of void can be expressed as

$$\dot{f}_v^{\text{nucleation}} = \frac{\beta X_M + f_N}{S_N\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\dot{\varepsilon}_{MT}^p - \varepsilon_{MT}}{\varepsilon_N}\right)\right] \dot{\varepsilon}_{MT}^p$$  \hspace{1cm} (16)

In the above equations, $\dot{\varepsilon}_{MT}^p$ represents the equivalent plastic strain in the matrix phase excluding the transformed martensite and $f_N$ refers to the volume fraction of the initial void nucleating particles. $X_M$ is the volume fraction of transformed martensite, which increases as the MIMT proceeds. Thus, $\beta X_M + f_N$ refers to the total volume fraction of the void nucleating sites, which increases as the MIMT proceeds. Here, $S_N$ represents the standard deviation and $\varepsilon_N$ represents the mean value of the normal distribution for the plastic strain controlled nucleation model [23]. The void nucleation parameters are chosen as $\beta = 0.25$, $f_N = 0.025$, $\varepsilon_N = 0.45$, and $S_N = 0.15$ [5]. The equivalent plastic strain in the matrix phase excluding the transformed martensite, $\dot{\varepsilon}_{MT}^p$, was calculated as the volume average of ones in the ferrite, bainite and retained austenite. Finally, the rate of increase of the void volume fraction, $\dot{f}_v$, can be calculated as

$$\dot{f}_v = f_{v}^{nucleation} + f_{v}^{growth}$$  \hspace{1cm} (17)

In this study, the following plastic instability condition for the onset of necking was employed to predict the uniform elongation and tensile strength in the uniaxial tensile test of the TRIP-aided multiphase steel.

$$\frac{d\sigma_e}{d\varepsilon^p} = \sigma_e$$  \hspace{1cm} (18)

In the above equation, $\sigma_e$ represents the equivalent plastic strain in the overall material.

5. Experimental

The chemical composition of the model alloy used to confirm the models suggested in Sections 2–4 is Fe–0.086C–4.92Mn–0.55Si–1.15Al–0.011P–0.0019S in wt%. The Ms temperature was estimated from Payson and Savage’s equation [24] considering the carbon enrichment in retained austenite. The steels were prepared by vacuum induction melting, followed by hot rolling to give 4 mm thick plates. After cooling to room temperature (in air), the plates were then cold rolled at a rolling reduction of 70%. The samples were then batch annealed at 645°C for 12 h, followed by air cooling to room temperature.

Uniaxial tension was applied to each sample using an Instron machine at strain rate of $1.3 \times 10^{-2}$/s. Each test specimen had a gauge length of 25 mm and width of 6 mm. An XRD method was used to measure the volume fraction of the martensite transformed before and after the tensile test.
Table 1
Materials constants for the flow curves of the 0.086C–4.92Mn–0.55Si–1.15Al–0.011P–0.0019S alloy steel.

<table>
<thead>
<tr>
<th>Constituent phase</th>
<th>K (MPa)</th>
<th>( \varepsilon_0 )</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austenite</td>
<td>1790</td>
<td>0.02</td>
<td>0.240</td>
</tr>
<tr>
<td>Ferrite + Bainite</td>
<td>955</td>
<td>0</td>
<td>0.247</td>
</tr>
<tr>
<td>Martensite</td>
<td>3191</td>
<td>0.01</td>
<td>0.210</td>
</tr>
</tbody>
</table>

6. Results and discussion

6.1. Deformation and transformation behavior of the model alloy

The initial texture of the retained austenite of the model alloy was assumed to be a random orientation. The values for all of the material property parameters used for the calculation are listed in Table 1. The hardening of the individual phases as a function of the accumulated plastic strain in each phase was represented by a Swift equation.

\[
\sigma_y = K(\varepsilon + \varepsilon_0)^n
\]  

(19)

The material's parameters for the MIMT were adjusted to give the best agreement between the calculated transformation kinetics data and the experimental data. The obtained parameter values are listed as Case II in Table 2.

Fig. 2(a) and (b) show the comparisons between the experimental data and the calculated results for the martensite fraction and the stress–strain curve of the model alloy. The material's parameters for the MIMT were adjusted to give the best agreement between the calculated transformation kinetics data and the experimental data. It can be confirmed that the martensitic transformation kinetics and the deformation behavior of the multiphase TRIP steel sheet can be successfully described by the model. The flow curve and the hardening rate, obtained using Eq. (18) are also presented in Fig. 2. As described in Section 4, the plastic instability condition of Eq. (18) was used to predict the onset of necking during the uniaxial tensile testing of the specimen. From the point of intersection between the two curves, the tensile strength and elongation of the specimen can be predicted. It can be seen that the proposed model simulates the experimental onset of necking excellently.

6.2. Prediction of strength/ductility of TRIP-aided multiphase steel

In order to design the phase combination of the TRIP-aided multiphase steel for the X-AHSS, five cases for the stability of the retained austenite were chosen, as shown in Fig. 3. The kinetics parameters for Fig. 3 are listed in Table 2. The values for the model alloy (in Table 1) were used as the mechanical properties of the material.

The flow curves and the hardening rates obtained using Eq. (18) for the various initially retained austenite fractions are presented in Fig. 4. In this calculation, the stability condition of the retained austenite of Case II was used. In comparison with the flow curve for the full F + B steel, the tensile strength of the TRIP-aided multiphase steel increases as the initial retained austenite fraction increases. This phenomenon is related to the volume fraction of the mechanically induced martensite phase. The increase in the fraction of hard martensite with increasing initial retained austenite fraction causes an increase in the hardening rate. In the case of the uniform elongation, it can be seen that the maximum value exists for the initial retained austenite fraction of 30%. This is related to

Table 2
Constants for the mechanically induced martensitic transformation in Eq. (3) under various instability conditions of the retained austenite.

<table>
<thead>
<tr>
<th>Constituent phase</th>
<th>( \delta )</th>
<th>( \alpha )</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>1.20</td>
<td>13.16</td>
<td>3.57</td>
</tr>
<tr>
<td>Case II</td>
<td>1.10</td>
<td>9.55</td>
<td>3.57</td>
</tr>
<tr>
<td>Case III</td>
<td>1.10</td>
<td>5.68</td>
<td>3.57</td>
</tr>
<tr>
<td>Case IV</td>
<td>1.10</td>
<td>2.99</td>
<td>3.57</td>
</tr>
<tr>
<td>Case V</td>
<td>1.10</td>
<td>1.64</td>
<td>3.57</td>
</tr>
</tbody>
</table>

Fig. 2. Comparison between calculated (solid lines) and measured (symbols) (a) martensitic volume fraction mechanically transformed and (b) flow curves during uniaxial tension of the 0.086C–4.92Mn–0.55Si–1.15Al–0.011P–0.0019S alloy steel. The point of intersection between the flow curve and the hardening rate of Eq. (18) indicates the onset of necking in the uniaxial tensile test of the specimen.

Fig. 3. Martensitic volume fraction mechanically transformed under various stability conditions of retained austenite corresponding to Table 2.
Fig. 4. Calculated flow curves and hardening rates under the conditions of various initial retained austenite fractions. The calculation was carried out for the austenite stability condition of Case II under the consideration of damage. The point of intersection between the flow curve and the hardening rate of Eq. (18) indicates the onset of necking in the uniaxial tensile test of the specimen.

Fig. 5. Flow curves and hardening rates calculated under the conditions with and without damage. The stability condition of the retained austenite of Case II and the condition of full austenite phase steel were used.

Fig. 6. Strength-ductility relationship calculated under the conditions with and without damage. The stability condition of the retained austenite of Case II was used. Fig. 6 shows the resulting prediction plotted as engineering uniform elongation versus ultimate tensile stress. Fig. 7(a) and (b) show

the negative effect of the mechanically induced martensite on the enhancement of uniform elongation [5,20,21]. When considering the increase in the void volume fraction due to void nucleation, the decohesion at the austenite–martensite interface (the area of which is increased due to the MIMT) might control the void nucleation of the TRIP-aided multiphase steel. In this study, this negative effect was dealt with by considering both the increase in the number of void nucleation sites due to the martensitic transformation, and the void growth based on the yield criterion for porous material. These two processes can be described by Eqs. (15) and (16), respectively.

In Fig. 5, the flow curve and the hardening rate of Eq. (18) calculated by considering the damage model are compared with those calculated without taking the damage model into account. In this calculation, the stability condition of the retained austenite of Case II and an entirely austenite phase steel were used. Both the tensile strength and the uniform elongation calculated with considering the damage are larger than those calculated without considering the damage. It is known that neglecting the damage in the material during plastic deformation and MIMT may cause the uniform elongation of the TRIP-aided steel to be overestimated [5].

Fig. 6 shows the resulting prediction plotted as engineering uniform elongation versus ultimate tensile stress. Fig. 7(a) and (b) show

Fig. 7. (a) Ultimate tensile stress and (b) uniform elongation calculated under the conditions with and without damage as a function of the initial austenite fraction. The stability condition of the retained austenite of Case II was used.
predictions of the ultimate tensile stress and uniform elongation as a function of the initial retained austenite fraction, respectively. The stability condition of the retained austenite of Case II was used with and without consideration of damage. It can be seen that the tensile strength of the TRIP-aided multiphase steel increases as the initial retained austenite fraction increases, irrespective of whether or not damage was considered. The uniform elongation tends to saturate to a specific value when no damage was considered. When damage was considered, a maximum value of uniform elongation exists, as shown in Figs. 6 and 7(b).

Fig. 8 shows a prediction of the strength–ductility balance, which is the multiplication of the tensile strength and elongation as the engineering measure, as a function of initial retained austenite fraction. The calculation was carried out with considering damage. In the relatively lower stability range of the retained austenite (Cases I–III), it can be seen that the strength–ductility balance of the multiphase TRIP-aided steel increases with increasing austenite stability. On the other hand, in the more stable austenite range (Cases IV and V), the strength–ductility balance of the multiphase TRIP-aided steel decreases with increasing austenite stability. That means that the optimum austenite stability should be determined to produce the most effective multiphase TRIP-aided steel.

Fig. 9 shows the final predictions plotted as engineering uniform elongation versus ultimate tensile stress in comparison with the strength–ductility balance map for the various steel sheets in this comparison. The contribution of post-uniform strain to the total elongation was ignored. However, since the uniform strain constitutes the majority of the useful strain under the uniaxial tension, this comparison may be valid. From this set of results, multiphase TRIP-aided steel with the desired strength–ductility balance can be designed.

7. Summary

In this research, a model that takes void nucleation and growth into account was used to thoroughly investigate the TRIP that accompanies the MIMT that occurs in multiphase TRIP-aided steel. The model used was a modified version of a microstructure-based computational model previously suggested for the study of two-phase austenitic steel [4].

To predict the uniform elongation during the uniaxial tensile testing of the multiphase TRIP-aided steel, the increase in the number of void nucleation sites due to the martensitic transformation and the void growth based on the yield criterion for porous material were studied. The plastic instability condition for the onset of necking was taken as the maximum-load criterion during the uniaxial tensile test. We conducted a tensile test on a low carbon multiphase TRIP-aided steel in order to validate the predictive capability of the model. The measured and calculated data were in good agreement with each other.

The feasibility of the X-AHSS was assessed by analyzing the results obtained using various initial volume fractions and various stabilities of the retained austenite in the TRIP-aided multiphase steel. The tensile strength in the TRIP-aided multiphase steel increased as the initial retained austenite fraction increases, irrespective of whether or not damage was considered. The uniform elongation tended to saturate to a specific value when no damage was considered. When damage was considered, a maximum value of uniform elongation exists. In the relatively lower stability of the retained austenite, the strength–ductility balance of TRIP-aided multiphase steel increased with increasing austenite stability. By contrast, in more stable austenite, the strength–ductility balance of the TRIP-aided multiphase steel decreased with increasing austenite stability. Finally, the optimum initial volume fraction and stability of the retained austenite in the TRIP-aided multiphase steel, which is corresponding to the appropriate value of the strength–ductility balance, could be designed.

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