High-speed Tensile Deformation Behavior of 1 GPa-grade TRIP-aided Multi-phase Steels

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DOI: http://dx.doi.org/10.2355/isijinternational.ISIJINT-2017-635
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1. Introduction

Transformation-induced plasticity (TRIP) is a strengthening mechanism that takes advantage of the deformation-induced martensitic transformation of retained austenite ($\gamma_R$) in steel. The TRIP effect is exploited for the manufacture of various steels such as TRIP-aided multi-phase (TRIP) steel\(^1\) and one potential application of TRIP steel is steel sheets for automobiles. Strength enhancement is important for the research and development on automotive steel plates in addition to the body weight reduction. Therefore, research is being pursued on the development of high-strength automotive steel sheets with tensile strength in the range of 1 to 1.5 GPa\(^,1,3-10\) A frequently used indicator of mechanical properties is the balance between strength and ductility, which is indicated by the relationship between tensile strength and total elongation. However, an important topic lies beyond this conventional strength–ductility balance argument, which is the development of steels in which strength can be enhanced without compromising on ductility.\(^3,4,6\) In addition, as collision safety is a necessary consideration for automotive steel sheets, investigation of high-speed tensile deformation behavior is important.\(^11-18\) The collision safety of a material can be understood better by investigating the tensile deformation behavior including the mechanical properties over a wide strain rate range, and comparing the results with those for existing materials. This study focuses on high-strength TRIP steel with 1 GPa-grade tensile strength. Mukherjee et al.\(^,19,20\) reported a 1 GPa class high-strength TRIP steel manufactured from 0.4 C steel, focusing on the effect of the matrix on the mechanical properties of TRIP steel. They manufactured TRIP steels from the same chemical composition but with different matrixes, conducted tensile tests under strain rates ranging from $3.33 \times 10^{-3}$ to $3.33 \times 10^{-2}$ s\(^{-1}\) at room temperature to 423 K. They discussed the relationship between the mechanical properties and changes in the deformation-induced transformation behavior with temperature and strain rate. Several reports, including those on TRIP and dual-phase (DP) steels, have considered a wide range of strain rates ranging from $10^{-3}$ to $10^{2}$ s\(^{-1}\), which is equivalent to that used in static tensile testing, to $10^{1}$ s\(^{-1}\), which in turn is equivalent to that for automobile collision.\(^11-15,17,18,21\) However, there are very few reports on 1 GPa-grade high-strength TRIP steels. Analysis of strength–elongation balance, which can be discussed in terms of tensile strength and total elongation for diverse steels and various strain rates, should play an important role in the development of next-generation automobile steel sheets.\(^13,17,18\)

In this study, we investigated the high-speed tensile deformation behavior and the strain rate dependencies of tensile properties of TRIP steel with 1 GPa-grade tensile strength. We also focused on the effect of $\gamma_R$ morphology on the tensile properties of high-strength TRIP steel, which is related to the
study by Mukherjee et al.\textsuperscript{19,20} The characteristics, potential, and drawbacks of the high-strength TRIP steel investigated in this study are discussed by comparing the obtained results to those previously reported for various steels.

2. Experimental Procedures

In this study, two types of TRIP steel with different $\gamma R$ morphologies were prepared from 0.3C-1.5Si-2Mn (mass%) steel and named needle-like $\gamma R$ steel and blocky $\gamma R$ steel. These TRIP steels were obtained by heating at 1 033 to 1 053 K and austempered at 673 K for 600 s followed by air-cooling using a cold rolled steel (blocky $\gamma R$ steel) and a steel sheet with martensite microstructure that was quenched after cold rolling (needle-like $\gamma R$ steel). Microstructures were observed using optical microscopy and scanning electron microscopy with electron backscatter diffraction (SEM-EBSD). A tint etching procedure was conducted in the optical microscope observations.\textsuperscript{22,23} The etchant was a mixture of the three ingredients 4% nital, 7% picral, and saturated aqueous sodium thiosulfate, which were mixed in an argon atmosphere. The specimen was etched at holding times between 10 and 20 s at temperatures between 293 and 298 K.\textsuperscript{13,22,23} The volume fraction of each microstructure including $\gamma R$ was derived from microstructure images and x-ray diffraction (XRD) results.\textsuperscript{13} Quantitative estimation for volume fraction of each phase in a mixture is proportional to the volume fraction of that phase.\textsuperscript{13,14}

Tensile tests were conducted at 296 K with various strain rates between $3.3 \times 10^{-6}$ s\textsuperscript{-1} and $10^3$ s\textsuperscript{-1} using 1 GPa-grade TRIP steels with different $\gamma R$ morphologies.\textsuperscript{12–14} The tensile test specimens were prepared such that the rolling direction becomes parallel. Tensile tests at high-speed strain rates between $3.3 \times 10^{-6}$ and $10^3$ s\textsuperscript{-1} were interrupted, and test specimens with various true strains (\(\varepsilon\)) were obtained.\textsuperscript{13,14} The volume fraction of the deformation-induced martensite was derived from XRD patterns obtained for specimens prepared with different \(\varepsilon\) and for specimens before tensile deformation and after fracture.\textsuperscript{13,14}

The carbon content of the $\gamma R$ ($C_{\gamma R}$ (mass%)) was calculated from the lattice constants for austenite ($a_1$) and ferrite ($a_0$) phases obtained by XRD experiments using the following equation:\textsuperscript{13,14,25}

$$
C_{\gamma R} = \left[ a_1 - \left( 3.572 \times a_0 / 2.8664 \right) \right] / 0.033 \quad \text{(1)}
$$

3. Results and Discussion

3.1. Microstructures of 1 GPa-grade TRIP-aided Multi-phase Steel

Figure 1 shows the optical micrographs of color etched 1 GPa-grade TRIP steels. White indicates $\gamma R$, blue indicates ferrite, and dark brown in Fig. 1(a) and brown in Fig. 1(b) indicate either bainite or martensite.\textsuperscript{13,22} Optical microscopy was performed on both color-etched and nital-etched specimens. From these observations, we found that the matrix of the needle-like $\gamma R$ steel in Fig. 1(a) is tempered martensite and partially bainite, while that of the blocky $\gamma R$ steel in Fig. 1(b) is ferrite and bainite. The volume fraction of $\gamma R$ ($V_{\gamma R}$) according to the XRD results was 24.6% for the needle-like $\gamma R$ steel and 22.9% for the blocky $\gamma R$ steel. In addition, the volume fraction of ferrite and bainite according to the point counting method in the optical images of the blocky $\gamma R$ steel was 39.7% and 37.4%, respectively. Figure 2 shows the SEM-EBSD inverse pole figures and phase maps of the two high-strength TRIP steels, revealing that the $\gamma R$ morphology is indeed needle and blocky shaped. In the phase maps, green and red indicate austenite and ferrite, respectively. Moreover, Figs. 2(c) and 2(d) show that $\gamma R$ is distributed in the ferrite grain boundaries and in bainite in the blocky $\gamma R$ steel.

| Shape of $\gamma$ | Retained austenite ($\gamma_R$) | Carbon content of $\gamma_R$ ($C_{\gamma_R}$) (mass%) |
|------------------|-------------------------------|-----------------------------------------------|
| Needle-like      | 24.6                          | 75.4 (martensite or bainite)                  |
| Blocky           | 22.9                          | 39.7 (ferrite) 37.4 (bainite)                 |

Table 1. Volume fractions of constituent microstructures and the carbon content of retained austenite in the 1 GPa-grade TRIP steels.

Fig. 1. Optical micrographs of the 1 GPa-grade TRIP steels with different $\gamma R$ shapes of needle-like (a) and blocky (b). (Online version in color.)

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summarizes the volume fractions of each microstructure and the carbon content of $\gamma_R$ in each type of TRIP steel.

3.2. Effect of Strain Rate on the Tensile Properties of 1 GPa-grade TRIP-aided Multi-phase Steel

Figure 3 shows the nominal stress–strain curves for the needle-like $\gamma_R$ steel (a) and the blocky $\gamma_R$ steel (b) obtained in the tensile tests under various strain rates. The yield strength increases with increasing strain rate in both TRIP steels, though the needle-like $\gamma_R$ steel shows a larger yield strength for the same strain rate. The strain rate dependency of the flow stress is small, and the change in the mechanical properties with the strain rate is larger for uniform elongation and total elongation. Figure 4 summarizes the 0.2% offset proof stress, tensile strength, and uniform elongation for different strain rates. Needle-like $\gamma_R$ steel shows a larger 0.2% offset proof stress for a given strain rate, as previously mentioned, but the strain rate dependency of 0.2% offset proof stress is nearly the same as that of blocky $\gamma_R$ steel. On the other hand, the tensile strength for a given strain rate is nearly independent of the $\gamma_R$ morphology and shows a similar strain rate dependence. The strain rate dependency of the tensile strength shows a slight decrease as the strain rate increases up to $10^3$ s$^{-1}$, and then increases as the strain rate exceeds this value. The tensile strength of steels mostly increases with increasing strain rate, for example, in TRIP steels obtained from 0.2C (0.21C-1.51Si-1.22Mn (mass%), $V_{\gamma_R}=10.6\%$) and 0.4C (0.41C-1.47Si-1.18Mn (mass%), $V_{\gamma_R}=16.0\%$) steels$^{13,14}$ and in DP (0.1C-0.1Si-1.0Mn-0.87Cr-0.25Mo (mass%)) steel.$^{15}$ However,
those for the 1 GPa-grade TRIP steels used in this study were different. Such the strain rate dependency of tensile strength has been observed in metastable austenitic stainless steels, which will be discussed later from the viewpoint of deformation-induced martensitic transformation behavior. The uniform elongation decreases with increasing strain rate. The needle-like γR steel gives a larger uniform elongation than the blocky γR steel for strain rates on the order of \(10^{-3} \text{ s}^{-1}\) or lower, and almost the same value at strain rates of \(10^0 \text{ s}^{-1}\) or higher. The needle-like γR steel indicates better uniform elongation in the low strain rate range, together with a larger change in the uniform elongation with the strain rate. Figure 5 shows the relationship between true stress and work-hardening rate versus strain rate with \(3.3 \times 10^{-4}\) (a) and \(3.3 \times 10^{-2} \text{ s}^{-1}\) (b). The point at which the true stress becomes identical to the work-hardening rate, or the plastic instability condition, appears as the tensile strength and uniform elongation in the nominal stress–strain curve. An increase in the work-hardening rate increases the value of strain rate with a larger change in the uniform elongation with the strain rate. Figure 5 shows the relationship between true stress and work-hardening rate as functions of true strain in the 1 GPa-grade TRIP steels with different γR shapes. (Online version in color.)

![Fig. 4](image_url)

**Fig. 4.** 0.2% offset proof stress, tensile strength and uniform elongation as functions of strain rate in the 1 GPa-grade TRIP steels with different γR shapes. (Online version in color.)

![Fig. 5](image_url)

**Fig. 5.** True stress and work-hardening rate as functions of true strain in the 1 GPa-grade TRIP steels with different γR shapes at the strain rates of \(3.3 \times 10^{-4} \text{ s}^{-1}\) (a) and \(3.3 \times 10^{-2} \text{ s}^{-1}\) (b). (Online version in color.)

larger in the blocky γR steel for any strain rate in the low strain rate range, but the work-hardening rate of the needle-like γR steel becomes larger when ε exceeds 0.15. In particular, the work-hardening rate remains almost the same when ε is between 0.1 and 0.2 in the case of the needle-like γR steel, at \(3.3 \times 10^{-4} \text{ s}^{-1}\). These results are similar to those reported for metastable austenitic stainless steels (TRIP effect by deformation-induced martensite) and Fe-30Mn-3Si-3Al steel (twinning-induced plasticity (TWIP) effect by deformation twinning). These indicate that in needle-like γR steel, the deformation-induced martensitic transformation of γR with the volume fraction of about 25% contributes to the stress–strain relationship as the TRIP effect. An increase in the strain rate to \(3.3 \times 10^{-2} \text{ s}^{-1}\) decreases the work-hardening rate at the same ε value for both steels. Comparing the change in the work-hardening rate with ε for the two γR morphologies, we found that it reversed when ε was about 0.15, similar to the results at \(3.3 \times 10^{-2} \text{ s}^{-1}\). The difference in the work-hardening rate at low ε is related to the work-hardening rate of the matrix microstructure. The fact that the work-hardening rate of the needle-like γR steel becomes larger than that of the blocky γR steel when ε exceeds 0.15 indicates that the TRIP effect due to deformation-induced transformation has a larger effect on the needle-like γR steel. However, the difference in work-hardening rate between the steels at high ε decreases as the strain rate increases. At \(10^0 \text{ s}^{-1}\) or higher, the uniform elongation for both TRIP steels decreases significantly, and the effect of the γR morphology on uniform elongation becomes smaller, as shown in Fig. 4. Such the change of uniform elongation is possibly related to the strain rate dependency of the work-hardening rate depicted in Fig. 5. The influence of the γR morphology and strain rate on the work-hardening rate seems to be mainly related to the deformation-induced transformation behavior of γR. The relationship between the deformation-induced martensitic transformation behavior and the tensile properties is discussed in the next section.

3.3. Effect of Strain Rate on Deformation-induced Martensitic Transformation Behavior of 1 GPa-grade TRIP Steel

Figure 6 shows the relationship between the volume fraction of the γR phase and strain rate.
fraction of deformation-induced martensite ($V_{a}$) and $\varepsilon$ for strain rates between $3.3 \times 10^{-6}$ and $10^{0} \text{s}^{-1}$. The plots in the figure denote XRD results, and the solid and dotted lines denoted the values calculated using the following equation,\(^{13,26}\) which is based on a relationship in Matsumura et al.'s paper,\(^{23}\) where $V_{a}$ is expressed as a function of $\varepsilon$.

$$V_{a} = V_{0} = \frac{V_{0}}{1 + (k/q)V_{0}^{q}}$$ \twodot \quad (2)$$

Here, $V_{0}$ is the volume fraction of $\gamma_{b}$ before deformation, $k$ and $q$ are constants.\(^{26}\) The constants of $k$ and $q$ in Fig. 6 are summarized in Table 2. The strain rate dependency of the deformation-induced transformation behavior indicates that $V_{a}$ increases with increasing strain rate for both TRIP steels when $\varepsilon$ is smaller than about 0.1. When $\varepsilon$ exceeds 0.1, the TRIP steels with needle-like and blocky $\gamma_{b}$ have the largest $V_{a}$ at a strain rate of $3.3 \times 10^{-4} \text{s}^{-1}$, and $V_{a}$ decreases when the strain rate is further increased to $3.3 \times 10^{-2}$ and $10^{0} \text{s}^{-1}.\(^{13,14,26}\) It is common knowledge that better uniform elongation can be obtained from the TRIP effect when a high transformation rate in the deformation-induced transformation can be maintained up to a large strain\(^{13,19,33–35}\). This is also the case for the present high-strength TRIP steels. However, the deformation-induced transformation behavior in the needle-like and blocky $\gamma_{b}$ steels at $3.3 \times 10^{-4} \text{s}^{-1}$ shows no significant difference, and this result alone cannot explain the differences in uniform elongation at low strain rates and in the work-hardening rate as seen in Fig. 5. Therefore, further investigations on the stress distribution among constituent microstructures, the stress–strain relationship for each phase, internal stress, and the influence of the morphology of $\gamma_{b}$ and deformation-induced martensite on the stress–strain relation\(^{25,36,37}\) should be necessary, in addition to understanding the deformation-induced transformation behavior. The maximum $V_{a}$ at maximum load point is at most 70% of the $\gamma_{b}$ volume fraction; as observed for TRIP steels thus far,\(^{13,14}\) not all of the $\gamma_{b}$ transforms into deformation-induced martensite at 296 K. Further improvement of the uniform elongation can be expected if an increase in $V_{a}$ at large strains or an increase in transformation rate can be achieved. For strain rates of $10^{0} \text{s}^{-1}$ or higher, where investigation of the deformation-induced transformation behavior as a function of $\varepsilon$ is difficult, the value of $V_{a}$ at fracture ($V_{af}$) was summarized as shown in Table 2 (It is difficult for the $V_{af}$ to discuss quantitatively because the value of $V_{af}$ is dependent on the position from fracture point and the specimen size. Here, the value of $V_{af}$ was shown as a reference data in terms of the deformation-induced transformation behavior during high-speed tensile deformation). The value of $V_{af}$ is nearly the same, irrespective of how much higher than $10^{1} \text{s}^{-1}$ the strain rate is. In other words, the change in $V_{af}$ with the strain rate is small in the high strain rates. Moreover, this $V_{af}$ is smaller than that at strain rates of $10^{0} \text{s}^{-1}$ and lower. This result is very similar to the strain rate dependency of the deformation-induced transformation behavior of metastable austenitic stainless steels\(^{24,26}\). As in the case of the TRIP steels used here, the tensile strength decreases with increasing strain rate up to $10^{3} \text{s}^{-1}$ and increases when the strain rate is increased beyond $10^{1} \text{s}^{-1}$. The uniform elongation significantly decreases when the strain rate is increased up to $10^{0} \text{s}^{-1}$. The change of uniform elongation became smaller for strain rates higher than $10^{3} \text{s}^{-1}.\(^{34,26}\) Comparison of the strain rate dependen-

Fig. 6. Volume fraction of deformation-induced martensite as a function of true strain at various strain rates between $3.3 \times 10^{-4} \text{s}^{-1}$ and $10^{0} \text{s}^{-1}$ in the 1 GPa-grade TRIP steels with $\gamma_{b}$ shapes of needle-like (a) and blocky (b). (Online version in color.)

### Table 2. Values of $k$, $q$ in Eq. (2) and $V_{af}$ of the fractured specimen ($V_{af}$) in the 1 GPa-grade TRIP steels with different $\gamma_{b}$ shapes at various strain rates.

| Strain rate ($\text{s}^{-1}$) | $k$     | $q$     | $V_{af}$ | $k$     | $q$     | $V_{af}$ |
|-----------------------------|--------|--------|----------|--------|--------|----------|
| $3.3 \times 10^{-6}$        | 13.3   | 0.82   | 0.183    | 5.9    | 0.55   | 0.122    |
| $3.3 \times 10^{-5}$        | –      | –      | 0.194    | –      | –      | 0.167    |
| $3.3 \times 10^{-4}$        | 24.4   | 0.922  | 0.211    | 32.7   | 1.04   | 0.167    |
| $3.3 \times 10^{-3}$        | –      | –      | 0.188    | –      | –      | 0.163    |
| $3.3 \times 10^{-2}$        | 5.0    | 0.524  | 0.174    | 20.7   | 0.82   | 0.153    |
| $1.0 \times 10^{0}$         | 8.19   | 0.6    | 0.160    | 9.23   | 0.55   | 0.171    |
| $1.0 \times 10^{1}$         | –      | –      | 0.149    | –      | –      | 0.123    |
| $1.0 \times 10^{2}$         | –      | –      | 0.147    | –      | –      | 0.128    |
| $1.0 \times 10^{3}$         | –      | –      | 0.158    | –      | –      | 0.112    |
cies of the tensile properties of 1 GPa-grade TRIP steels in this study with the results obtained for metastable austenite steel reveals that the decrease in tensile strength and uniform elongation with increasing strain rate up to $10^3$ s$^{-1}$ is strongly affected by the reduction in $V_{\text{a}}$. On the other hand, as the change in $V_{\text{a}}$ and deformation-induced transformation behavior at strain rates above $10^3$ s$^{-1}$ is small, the effect of increasing strain rate on the tensile properties is more profound than the deformation-induced transformation (or TRIP effect); this explains the increased tensile strength and decreased variation in the uniform elongation at high strain rates. The fact that the strain rate dependencies of the tensile strength and uniform elongation of the TRIP steels at high strain rates is similar to the results for DP steel also supports the above discussion for high strain rates. In summary, the strain rate dependencies of the tensile strength and uniform elongation of the TRIP steels at high strain rates is similar to the results for DP steel also supports the above discussion for high strain rates. In summary, the strain rate dependencies of the tensile strength and uniform elongation of the TRIP steels at high strain rates is similar to the results for DP steel also supports the above discussion for high strain rates.

### 3.4. Comparison of Tensile Deformation Behavior in 1 GPa-grade TRIP-aided Multi-phase Steel and Other Steels

The tensile test results for the 1 GPa-grade TRIP steels examined in this study are compared with those for various other steels, and the strain rate dependencies of the tensile properties and high-speed tensile deformation behavior of the TRIP steels are discussed. Figure 7 shows the relationship between the tensile strength and total elongation obtained from the tensile tests for the 1 GPa-grade TRIP steels and various other steels at strain rates of $3.3 \times 10^{-4}$ and $10^3$ s$^{-1}$. Tensile test specimens with the same shape that were tested using the same machine were used for each strain rate in the results for the two strain rates shown in Figs. 7 and 8. The $\gamma_R$ morphologies of the 0.2 C and 0.4 C TRIP steels discussed in this section are blocky. From the results in Fig. 7(a) for a strain rate $3.3 \times 10^{-4}$ s$^{-1}$, the needle-like $\gamma_R$ steel has a tensile strength of 1 GPa and total elongation of 40%, which are superior to those existing TRIP steel (for example, 0.2 C TRIP

![Fig. 7. Relationships between tensile strength and total elongation in the 1 GPa-grade TRIP steels with different $\gamma_R$ shapes and various steels at $3.3 \times 10^{-4}$ s$^{-1}$ (a) and $10^3$ s$^{-1}$ (b). (Online version in color.)](image)

![Fig. 8. Relationships between tensile strength and uniform elongation in the 1 GPa-grade TRIP steels with different $\gamma_R$ shapes and various steels at $3.3 \times 10^{-4}$ s$^{-1}$ (a) and $10^3$ s$^{-1}$ (b), (c). (Online version in color.)](image)
steel\(^{13}\) in Fig. 7), because 1 GPa-grade strength is achieved while maintaining high total elongation. When comparing with the results for a strain rate of \(10^3\) s\(^{-1}\), we must note that the effect of the specimen size on the total elongation along the longitudinal direction is larger at a strain rate of \(10^2\) s\(^{-1}\), because the specimen size (gage length of the parallel section) is different at different strain rates. However, the product of tensile strength and total elongation is almost the same or higher, except for the metastable austenite steel (SUS304 and SUS301L\(^{23,26}\)) and needle-like \(\gamma_R\) steel. The local elongation, in particular, is strongly influenced by the specimen size; a larger local elongation is found at \(10^3\) s\(^{-1}\) \(^{28}\) because the gage length is smaller. Therefore, the results are summarized with uniform elongation, which is the ductility in uniform deformation, in place of the total elongation. Figure 8 shows the relationship between tensile strength and uniform elongation. As seen in Fig. 8, the results for the needle-like \(\gamma_R\) steel are better than those for other TRIP steels and DP steels at a strain rate of \(3.3 \times 10^{-4}\) s\(^{-1}\). However, at a strain rate of \(10^3\) s\(^{-1}\), the product of tensile strength and uniform elongation decreases, except for DP steels. Among these results, the decrease in \(V_{UL}\) with increasing strain rate greatly influences changes in the tensile strength and uniform elongation for the four TRIP steels and metastable austenite steel.\(^{13,14,24,26}\) For IF steel,\(^{38}\) which is a single-phase ferrite steel, the significant decrease in uniform elongation is caused by the following factors. The work hardening in the ferrite microstructure is smaller than those for TRIP and DP steels. Temperature rise of a specimen during adiabatic deformation cannot be neglected in the high strain rates and the amount of the thermal stress component, which is related to temperature and strain rate dependencies of flow stress, is large in the IF steel.\(^{39,40}\) The \(\gamma_R\) morphology and deformation-induced transformation behavior should not have any significant influence on the tensile properties of high-speed deformation, because the two types of 1 GPa-grade TRIP steel show almost the same values at a strain rate of \(10^4\) s\(^{-1}\). Figure 8(c) shows an enlarged view of the region where the tensile strength is larger than 800 MPa and uniform elongation is smaller than 30% in Fig. 8(b). The results for the strain rate of \(10^3\) s\(^{-1}\) are reorganized by focusing on steels with 1 GPa-grade tensile strength at \(10^3\) s\(^{-1}\). The needle-like and blocky \(\gamma_R\) steels show a good tensile strength–uniform elongation relationship, although this is inferior to that of metastable austenite steel. Figure 9 summarizes the product of tensile strength and uniform elongation as a function of strain rate for the four steels with 1 GPa-grade tensile strength (needle-like \(\gamma_R\), blocky \(\gamma_R\), 0.4 C TRIP,\(^{14}\) and 0.15 C DP\(^{15}\)), for a detailed comparison of the strain rate dependencies of the tensile properties for the strain rate of \(10^3\) s\(^{-1}\). The 0.15 C DP steel shows almost constant values, although there is a slight variation, regardless of the strain rate. The three types of TRIP steel show better results in the low strain rate range as compared to the DP steel, but the difference among the DP and three TRIP steels becomes smaller above \(10^2\) s\(^{-1}\). This result also shows that the TRIP effect contributes more effectively at low strain rates than at high strain rates. The differences between the three TRIP steels decrease at strain rates of \(10^0\) s\(^{-1}\) and higher, but the results for the needle-like \(\gamma_R\) steel and blocky \(\gamma_R\) steel are better than those for 0.4 C TRIP steel.\(^{14}\) This is due to the difference in uniform elongation, as shown in Fig. 8. Therefore, a large volume fraction of \(\gamma_R\) plays a certain role in a large uniform elongation under high-speed tensile deformation, even though the deformation-induced transformation behavior is suppressed at high strain rates. From a different perspective, superior TRIP effects at low strain rates will affect the tensile properties at high strain rates to a certain degree; a \(R_{\gamma}\) value higher than that of currently available steels is expected to improve uniform elongation and increase tensile strength. This study clarified that when the \(\gamma_R\) volume fraction exceeds 20\%, the strain rate dependencies of tensile properties changes from that of conventional TRIP and DP steels to that of metastable austenitic stainless steel, and that this change is caused by deformation-induced transformation behavior. These insights will inspire future discussion on high-strength TRIP steels. Furthermore, investigation from different viewpoints on the strengthening mechanisms that lead to excellent high-speed deformation behavior would be necessary when considering the advantages or limitations of the TRIP effect for the high-speed tensile deformation behavior. This study shows that the TRIP effect contributes very effectively to the improvement of mechanical properties at low strain rates. It is considerable of the present results that the tensile deformation behavior for the high strain rates are poor comparing with those for a low strain rate. However, there is much to be understood regarding the mechanical properties, with emphasis on the high strain rate deformation, for crash safety evaluation. Therefore, future research topics include understanding the effectiveness of strengthening mechanisms, such as the TRIP effect, and further improvement of the mechanical properties during high-speed deformation by an in-depth focused of the tensile properties at high strain rates, as shown in Fig. 8(c).

Figure 10 shows the relationship between the absorbed energy under 10% strain at \(10^2\) s\(^{-1}\) versus yield strength at strain rate of \(10^4\) s\(^{-1}\) order.\(^{13-16}\) The absorbed energy under 10% strain was chosen because of reports that high-speed deformation at strain rates \(<10\%\) dominates impact energy.

![Graph showing the relationship between absorbed energy and yield strength](image-url)
absorption according to the impact crash analysis of square tubes that simulate front-side members that absorbed energy and reduce impact force during an automobile collision.\(^5\)\(^-\)\(^8\)\)

Again, the results for various steels\(^12\)\(^-\)\(^16\) are summarized (FC, FP, D mean ferrite-cementite, ferrite-pearlite and average ferrite grain size, respectively). The absorbed energy increases with increasing yield strength. We find that the yield strength is an important mechanical property for absorbed energy, and that an increase in yield strength leads to an increase in absorbed energy up to 10% strain. Similar results are reported for cases where the strain is summarized by the flow stress at 5% strain, which simulates deformation resistance during press forming.\(^6\)\(^-\)\(^8\),\(^10\)\)

The total elongation is an index of workability, and the relationship between workability and collision safety can be achieved by using needle-like \(\gamma_r\) steel in automotive steel sheets. In the future, it is important to conduct quantitative analyses for the improvement of energy absorption, collision safety, and strength by carrying out similar investigations on various steels.

4. Conclusion

This study investigated the high-speed tensile deformation behavior and the effect of strain rate on tensile properties of two types of TRIP-aided multi-phase steels with 1 GPa-grade strength and different retained austenite (\(\gamma_r\)) shape. The main results are as follows.

(1) TRIP-aided multi-phase steel with a needle-like \(\gamma_r\) shape has a tensile strength of 1 GPa and about 40% total elongation in a static tensile test with a strain rate of \(3.3 \times 10^{-3}\) s\(^{-1}\). This has the same total elongation as known TRIP steels, but the strength is larger; therefore, better tensile properties can be obtained. Comparison of the mechanical properties of two types of high-strength TRIP steels with different \(\gamma_r\) morphologies showed that the needle-like \(\gamma_r\) steel has a larger 0.2% offset proof stress for the same strain rate and larger uniform elongation at low strain rates of less than \(10^{-3}\) s\(^{-1}\).

(2) Uniform and total elongations, in both TRIP steels and various steels, but the strength is larger; therefore, better tensile properties can be obtained. Comparison of the mechanical properties of two types of high-strength TRIP steels with different \(\gamma_r\) morphologies showed that the needle-like \(\gamma_r\) steel has a larger 0.2% offset proof stress for the same strain rate and larger uniform elongation at low strain rates of less than \(10^{-3}\) s\(^{-1}\).

(3) The tensile properties of needle-like \(\gamma_r\) steel are better than those of other steels, as seen from the compari-
son of the tensile deformation behavior with other steels at various strain rates. Absorbed energy, which is related to the collision properties of automobiles, increases with increasing flow stress at small strain such as yield strength. The needle-like γf steel indicated high strength, better workability and collision safety from the relationship between absorbed energy up to fracture and total elongation at the static tensile tests.

Acknowledgments
This study was obtained as a result of a commissioned project by a New Energy and Industrial Technology Development Organization (NEDO), and the support is greatly appreciated. The authors are also grateful to Dr. Y. Tanaka of JFE steel, Prof. Y. Tanaka of Kagawa University, Prof. H. Adachi of University of Hyogo and Dr. R. Ueji of National Institute for Materials Science for their helps.

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