Effects of Tramp Elements on Formability of Low-carbon TRIP-aided Multiphase Cold-rolled Steel Sheets

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Four kinds of TRIP-aided cold-rolled steel sheets were fabricated with additions of tramp elements of Cu, Cr, and Ni to a basic 0.15C–1.5Mn–1.5Si–0.5Cu (hereafter all in wt%) steel, and their microstructures, mechanical properties, and formability were investigated to analyze the effects of the addition of tramp elements. These steel sheets were intercritically annealed at 780–790°C, and isothermally treated at 430°C. Tensile tests and limiting dome height (LDH) tests were conducted, and the changes of retained austenite volume fractions as a function of tensile strain were measured using X-ray diffraction. The formability of the Cu- and Ni-containing cold-rolled steel sheets was greatly improved as the strain-induced transformation of retained austenite was sustained up to the high strain region due to their high volume fraction and stability of retained austenite. On the other hand, the Cr-containing steel sheets showed a dual-phase structure of ferrite and martensite resulting from low volume fraction and stability of retained austenite and a large amount of transformed martensite. These findings indicated that when tramp elements such as Cu, Cr, and Ni were positively used, low-carbon TRIP-aided cold-rolled steel sheets having mechanical properties suitable for various application purposes and excellent formability could be successfully achieved.

KEY WORDS: TRIP steel; tramp element; formability; retained austenite; strain-induced transformation.

1. Introduction

Cold-rolled steel sheets, which show excellent ductility and formability in spite of somewhat low strength, have been preferred in automotive industries because there are some technical manufacturing problems including the difficulties involved in forming sheets.^{1–4)} However, the world-wide attention to environmental issues is seriously calling for enhancement in fuel efficiency, reduction of emission gas, and better recycling of resources as well as improved driving performance and safety.

Recently, TRIP (transformation induced plasticity)-aided steels are recognized as new concept steels, in which both high strength and high ductility can be achieved from the strain-induced transformation of retained austenite.^{5,6)} Particularly, C–Si–Mn TRIP-aided cold-rolled steel sheets, whose basic structure is composed of ferrite, bainite, and retained austenite, have simpler alloying elements and are more applicable to various heat treatments. They are evaluated to have excellent recyclability as well as high strength and ductility,^{1,7)} and thus are expected to be widely applied as structural materials for automobiles in the future.

One of the new directions currently undertaken in the development of new steels aiming at improved mechanical properties and better recyclability is the positive application of tramp elements. Tramp elements refer to those retained and stored inside steels since they are not easily eliminated even in the refining process, which is one of the important process in steel scrap recycling. They are generally known

to deteriorate mechanical properties, tensile properties in particular.^{8–12)} However, some representative tramp elements such as Cu, Cr, and Ni can be favorably applied to improve mechanical properties of steels. Therefore, positive application of them can contribute to the development of excellent advanced steels and to the more efficient use of resources. One example is the addition of a small amount of Cu to steels, which was reported to promote the precipitation strengthening due to the precipitation of several nanometer-sized quasi-stable 9R phases of orthorhombic structure or stable ϵ -Cu particles of face centered cubic structure.^{11,13)} Also, recent studies presented enhanced mechanical properties by Cu addition to TRIP-aided steels.^{11,14–16)} It was also confirmed that the containment of tramp elements Cu, Cr, and Ni in TRIP-aided cold-rolled steel sheets could work favorably for the enhancement of mechanical properties.¹⁵⁾ Despite the generally accepted knowledge of excellent mechanical properties of TRIP-aided steels, TRIP-aided cold-rolled steel sheets in particular, studies on the formability are yet to come.

In the present study, the effects of tramp elements on the formability were investigated in TRIP-aided cold-rolled steel sheets, to which Cu, Cr, and Ni were added alone or in combination. This study also provided the basic data for the development of high-strength and high-formability TRIP-aided cold-rolled steel sheets through active utilization of tramp elements.

2. Experimental

Four kinds of 0.8-mm-thick cold-rolled steel sheets (basic composition; 0.15C–1.5Mn–1.5Si–0.5Cu (wt%)) with addition of 0.4% Cr and Ni, either alone or in combination, were fabricated by vacuum induction melting, hot rolling, and cold rolling. They are referred to as ECO-6, 7, 8, and 9 steel sheets, whose chemical compositions are listed in **Table 1**. Based on the results from various heat-treatment conditions, those showing the most excellent mechanical properties were chosen; that is, 5-min intercritical annealing at 780–790°C where the volume fraction ratio of ferrite and austenite is 50:50, 3-min isothermal treatment at 430°C, and then air-cooling.

The heat-treated cold-rolled steel sheets were first etched in a 4% nital solution, etched again in a sodium metabisulfite solution ($\text{Na}_2\text{S}_2\text{O}_3 \cdot \text{H}_2\text{O}$ 10 g + H_2O 100 mL),¹⁴⁾ and observed by an optical microscope. Room-temperature tensile tests were conducted on plate-type specimens (longitudinal direction) with a gage length of 25 mm and a gage width of 6.3 mm at a crosshead speed of 2.5 mm/min. Engineering stress–strain curves were obtained from the tensile test, and then were converted to true stress–true strain curves to determine the strain hardening exponent, n , in the uniform strain range from 5 to 20%. After the tensile specimens were deformed at 15%, the thickness and width of the gauge section before and after the deformation were measured to obtain the plastic strain ratio, r .

$$r = \varepsilon_0 / \varepsilon_f = \ln(w_0/w_f) / \ln(t_0/t_f) \dots\dots\dots (1)$$

Here, w and t refer to the width and the thickness of the gauge section, respectively, while the subscripts 0 and f refer to pre- and post-deformation, respectively.

Volume fraction of retained austenite was measured using an X-ray diffractometer. Specimens were prepared by polishing both mechanically and chemically sheets into half of the thickness. Mo- K_α characteristic ray was used, and the volume fraction of retained austenite, V_γ , was calculated from the integrated intensity of ferrite and austenite peaks using the equation, $V_\gamma = 1.4I_\gamma / (I_\alpha + 1.4I_\gamma)$.^{17,18)} Here, I_γ is the average integrated intensity obtained at 220 $_\gamma$ and 311 $_\gamma$ peaks, and I_α is that obtained at 211 $_\alpha$ peak. Stability of retained austenite was also evaluated by a strain-induced martensitic transformation rate formula, which was recently suggested by Chung¹⁹⁾ and Chang *et al.*²⁰⁾.

$$\log[\ln f_s / (f_s - f)] = \log \kappa + m \log \varepsilon \dots\dots\dots (2)$$

where f_s and f refer to the saturated martensite volume fraction and the martensite volume fraction transformed during deformation, respectively, while ε and m refer to the true strain and the deformation mode coefficient, respectively. κ is defined to be the stability coefficient of retained austenite.

In order to evaluate the formability of the cold-rolled steel sheets, limiting dome height (LDH) tests were conducted using a hemispheric punch. A schematic diagram of this LDH test is shown in **Fig. 1**. Minimum limiting dome height, LDH_0 , was obtained from 200-mm-long rectangular specimens with varying width. The rectangular specimens were marked with circular grids by electro-chemical etching method, and were deformed until either local necking or

Table 1. Chemical compositions of cold-rolled steel sheets used. (wt%)

Steel	C	Si	Mn	Cu	Cr	Ni	Fe
ECO-6	0.14	1.49	1.51	0.51	-	-	Bal.
ECO-7	0.15	1.52	1.51	0.51	0.39	-	Bal.
ECO-8	0.15	1.53	1.52	0.51	-	0.41	Bal.
ECO-9	0.15	1.55	1.50	0.50	0.39	0.41	Bal.

Fig. 1. Schematic diagram of the limiting dome height (LDH) test.

fracture occurred. The forming limit curve (FLC) was drawn by measuring major strain, ε_1 , and minor strain, ε_2 , together with the strains of the locally necked region and the un-necked region, using an optical grid analyzer after the limit strain was established.

3. Results

3.1. Microstructure

Figures 2(a) through **2(d)** are optical micrographs of the four heat-treated cold-rolled steel sheets. These specimens were intercritically annealed for 5 min at temperatures where the volume fraction ratio of ferrite and austenite is 50:50; 780°C for the ECO-6 and ECO-7 steels, and 790°C for the ECO-8 and ECO-9 steels. When the specimens are etched by a sodium metabisulfite solution, it is easier to define the phases since ferrite is displayed as gray, bainite or martensite as black, while retained austenite as white.¹⁴⁾ In all the steels, most retained austenites are connected with adjacent ferrites, bainites, or martensites, while some are isolated in ferrite grains. There are some film-type retained austenites located in bainite or martensite lath boundaries, although they are not easily identified in **Figs. 2(a)** through **2(d)**. Volume fractions of retained austenite vary with steels, being about 15% in the ECO-6 steel, about 16% in the ECO-8 steel, and below 10% in the ECO-7 and ECO-9 steels.

3.2. Mechanical Property and Retained Austenite Volume Fraction

Table 2 summarizes tensile properties and volume fractions of retained austenite for the four steels. Yield strength of the ECO-6 and ECO-8 steels is about 500 MPa, and that of the ECO-9 steel is slightly lower than this. The ECO-7 steel shows the lowest yield strength of about 420 MPa. Tensile strength of the ECO-7 and ECO-9 steels is high at around 1 000 MPa, and that of the ECO-6 and ECO-8 steels

Fig. 2. Optical micrographs of the (a) ECO-6, (b) ECO-7, (c) ECO-8, and (d) ECO-9 steels. Etched by 4% nital and 10% sodium metabisulfite solutions.

Table 2. Room-temperature tensile properties and volume fraction of retained austenite of cold-rolled steel sheets.

Steel	Y.S. (MPa)	T.S. (MPa)	Elong. (%)		TS×Elong. GPa·%(Total)	<i>n</i>	<i>r</i>	<i>V_{γ0}</i> (%)
			Uniform	Total				
ECO-6	505	817	28.4	36.4	29.7	0.28	0.93	14.7
ECO-7	425	990	14.9	20.4	20.1	0.19	0.77	8.9
ECO-8	492	838	25.4	32.0	26.8	0.26	0.88	16.2
ECO-9	486	1066	13.7	18.1	19.3	0.16	0.87	8.5

is low at about 820 MPa. In the case of total elongation, the ECO-6 and ECO-8 steels show high elongation above 30%, but the ECO-7 and ECO-9 steels show low elongation less than 20%. This trend also holds in the case of uniform elongation. Strain hardening exponents, *n*, of the ECO-6 and ECO-8 steels are relatively high at 0.28 and 0.26, respectively, whereas the ECO-7 and ECO-9 steels have low *n* values less than 0.20. Plastic strain ratio, *r*, is the highest in the ECO-6 steel at 0.93, and the lowest in the ECO-7 steel at 0.77. Those of the ECO-8 and ECO-9 steels are 0.88 and 0.87, respectively.

The changes in work hardening rate, $d\sigma/d\varepsilon$, as a function of true strain are shown in **Fig. 3**. The $d\sigma/d\varepsilon$ of the ECO-6 and ECO-8 steels gradually decreases up to the true strain of 0.25, and the ECO-6 steel shows the highest level of $d\sigma/d\varepsilon$ in the region of true strain 0.10 and above. The $d\sigma/d\varepsilon$ of the ECO-7 and ECO-9 steels is abruptly reduced with increasing true strain, and deformation is terminated at the low strain of about 0.15. These data indicate that the

Fig. 3. Work hardening rate, $d\sigma/d\varepsilon$, as a function of true strain.

ECO-6 and ECO-8 steels would show better formability because of their more excellent uniaxial elongation than the other two steels.

Mechanical properties, particularly tensile elongation and values of *n* and *r*, are closely related with retained austenite volume fraction. To produce TRIP effect, it is generally known that the volume fraction of retained austenite should be more than 10%.^{21,22)} In consideration of this, the ECO-6 and ECO-8 steels, having retained austenite volume fraction of more than 15%, are expected to show sufficient TRIP effect. In other words, higher retained

Fig. 4. SEM micrograph of the ECO-9 steel, showing the formation of martensite having lath structure.

Fig. 5. Volume fraction changes of retained austenite as a function of true strain.

austenite volume fraction can lead to increased tensile elongation due to the strain-induced transformation, which also brings the higher values of n and r . On the other hand, the ECO-7 and ECO-9 steels have very low retained austenite volume fractions. **Figure 4** is an SEM micrograph of the ECO-9 steel. In this figure, it can be seen lots of martensite with lath structure. The same was confirmed in the ECO-7 steel. This indicates that in the cases of the ECO-7 and ECO-9 steels, in which a large amount of martensite is formed during cooling before or after the isothermal treatment, the volume fraction of retained austenite is reduced, and the TRIP effect is overridden by the dual phase strengthening effect; thus, showing high strength but low ductility.

3.3. Stability of Retained Austenite

Figure 5 presents the changes in volume fraction of retained austenite as a function of true strain. In the ECO-9 steels, the volume fraction of retained austenite dramatically drops in the initial strain region below 0.05, and it hardly changes in the strain region of 0.07 and above. In the ECO-6 and ECO-8 steels, it is abruptly reduced up to the true strain of 0.12, after which it shows a mild reduction, indicating that the martensitic transformation is in progression up to the strain of 0.25.

Fig. 6. Martensite transformation ratio changes as a function of true strain.

Fig. 7. Relationship between $\log[\ln f_s/(f_s - f)]$ and $\log \epsilon$. The deformation mode coefficient as represented by the slope, m , is 1.0.

Figure 6 shows the martensite transformation ratio converted from the changes in retained austenite volume fraction of Fig. 5 as a function of true strain. In the ECO-6 and ECO-8 steels, the martensitic transformation persists up to the high strain region of 0.25, and the martensite transformation ratio of the ECO-8 steel in the low strain region below 0.1 is higher than that of the ECO-6 steel, after which both show similar values. Although the martensite transformation ratio of the ECO-7 steel shows the same pattern as that of the ECO-8 steel, the ECO-7 steel shows the higher martensite transformation ratio overall in the strain region of 0.16 or below. Unlike other steels, in the ECO-9 steel, the martensitic transformation reaches the saturation at the strain of about 0.05. In the ECO-7 and ECO-9 steels, however, the martensitic transformation is terminated at the strain of about 0.18.

The relationship between $\log \epsilon$ and $\log[\ln f_s/(f_s - f)]$ was interpreted by applying Eq. (2) to the results of Fig. 5, and is graphed in **Fig. 7**. The saturated volume fraction of martensite was measured to be 12.1% in the ECO-6 steel, 6.8% in the ECO-7 steel, 13.8% in the ECO-8 steel, and 6.8% in the ECO-9 steel, respectively. The slope of straight lines, m , in Fig. 7 and Eq. (2), being the deformation mode

coefficient, equals 1.0 in C-Si-Mn TRIP-aided steels, and is known to have specific values depending on alloying compositions.¹⁹⁾ The stability coefficient of retained austenite, κ , is low in the ECO-6 steel, and increases in the order of the ECO-8, ECO-7, and ECO-9 steels. It is thus found that the ECO-6 steel has the most stable retained austenite, whereas the ECO-9 steel has the least stable retained austenite.

3.4. Formability

Figure 8 shows the results of the minimum limiting dome height, LDH_0 , measured under plane strain and dry lubrication conditions. Generally, in the results from the limiting dome height (LDH) test, LDH_0 depends on the specimen width, and typically exists when the specimen width ranges from 126 to 132 mm in cold-rolled steel sheets for automobiles.²³⁾ Here, LDH_0 is a barometer of the formability of steel sheets used in the stamping process, and thus the higher LDH_0 indicates the better formability.²³⁾ According to Fig. 8, the LDH_0 of the ECO-6 steel is 27.2 mm at the specimen width of 129 mm, implicating that it has the best formability. On the contrary, in the ECO-7 and ECO-9 steels, LDH_0 values are around 20 mm, and particularly the ECO-9 steel has the worst formability.

Figure 9 shows forming limit curves (FLCs) obtained from the measurements of the deformed circular grids by

Fig. 8. Bar graphs showing minimum limiting dome height, LDH_0 , measured under plane strain and dry lubrication conditions.

Fig. 9. Forming limit curves obtained from the measurements of the deformed circular grids by an optical grid analyzer.

an optical grid analyzer. In general, the higher FLC is evaluated as the better formability, and the value of the limit plane strain, FLC_0 , corresponding to the lowest point in a plane strain mode of $-0.1 < \epsilon_2 < 0.2$ typically indicates a typical barometer used to evaluate the formability.^{24,25)} The ECO-6 steel having the highest FLC_0 and the ECO-8 steel showing similar value as the ECO-6 steel are considered to have excellent formability. The ECO-7 and ECO-9 steels whose FLC_0 values are much lower than those of the ECO-6 and ECO-8 steels have poor formability.

4. Discussion

4.1. Correlation of Strain-induced Transformation and Formability

According to earlier studies concerned with TRIP-aided cold-rolled steel sheets, the stability as well as the volume fraction of retained austenite have been recognized as important factors directly affecting the strain-induced transformation behavior and ductility enhancement. According to Matsumura's study⁷⁾ on this, the ductility enhancement of steel sheets containing retained austenite results from the delayed occurrence of necking up to high strain region as the strain hardening of ferrite grains is recovered when the stress concentration is relaxed by the strain-induced transformation of retained austenite during plastic deformation. When ferrite, bainite, and retained austenite coexist, closer examination of the strain-induced transformation of retained austenite indicates that ferrite is strain-hardened and that strain energy is accumulated in ferrite grains due to dislocation pile-up. The accumulated strain energy here provides the driving force required for the strain-induced transformation of retained austenite to martensite.²⁶⁾ Upon the occurrence of strain-induced transformation, this energy is absorbed, and is accompanied by the relaxation of dislocation pile-up and the softening of ferrite grains. Afterwards, the softened ferrite grains are strain-hardened again by martensite, and this process repeats while the strain-induced transformation of retained austenite continues on. Since resistance to deformation is large when retained austenite is stable, the strain-induced transformation of retained austenite can proceed quite steadily even under high strains, thereby preventing abrupt deterioration of strain hardenability and delaying the occurrence of necking up to the high strain region.

For this reason, the ECO-6 and ECO-8 steels having higher stability of retained austenite show high strain hardening exponent and high tensile and uniform elongation, together with high strength above 800 MPa. On the other hand, the ECO-7 and ECO-9 steels have ultra-high strength above 1 000 MPa, low tensile elongation of about 20%, and high strain hardenability in the beginning of deformation as described in Table 2 and Fig. 3, and thus have similar properties to those of dual phase steels. This is because in the ECO-7 and ECO-9 steels, the strain-induced transformation proceeds rapidly in the initial stage of deformation as they have a large amount of martensite (Fig. 4) and also show the low volume fraction and stability of retained austenite. This strain-induced martensite transformation behavior directly affects the formability.

In general, in sheet metal forming, the formability is

mainly evaluated by plastic strain ratio, r , and strain hardening exponent, n . Keeler and Backofen²⁷⁾ reported that the higher n in press forming indicated the more homogeneous strain and the higher stretching performance. Whiteley,²⁸⁾ based on the results from deep drawing tests of round blanks, confirmed that the increase in the averaged value of r was accompanied with the increased limit drawing ratio. Actual investigation into the formability of each steel sheet reveals that the ECO-6 and ECO-8 steels have not only higher strain hardening index and plastic strain ratio than the other two steel sheets (Table 2) but also higher values of LDH_0 and FLC_0 , thereby confirming the better formability of them. As discussed earlier, this is because the strain-induced martensite transformation and strain hardening continue up to the high strain region beyond 0.25 due to the high stability of retained austenite.

4.2. Effects of Added Elements

This study confirms that the added tramp elements directly affect the volume fraction and stability of retained austenite and the strain-induced transformation, and thus determine the mechanical properties and formability of steel sheets. The Cu-added ECO-6 steel, having relatively high retained austenite volume fraction of about 15% and the lowest stability coefficient, shows the best tensile properties and formability. Cu, as an austenite stabilizer, works favorably for the formation of retained austenite and accordingly for the increase in its volume fraction accompanied with the enhancement of mechanical properties. Authors previously reported on the considerable enhancements achieved with a 0.15C–1.5Si–1.5Mn low-carbon TRIP-aided cold-rolled steel sheet by adding 0.5% Cu to it, which had highly increased retained austenite volume fraction, equal level of stability, and improved tensile elongation, formability, and strengths.²⁹⁾ Besides, it is known that ferrite grain strengthening can be achieved by a small amount of Cu addition because fine 9R or ϵ -Cu particles are precipitated in ferrite grains.^{11,13)} This can be a way to reduce the hardness gap between the soft ferrite and the hard bainite or martensite, which has long posed a problem in forming TRIP-aided cold-rolled steel sheets. In the case of 1.0% Cu addition, it was generally reported that the effect of precipitation strengthening was visible only when aged for several tens of minutes in the temperature range from 400 to 700°C.^{30,31)} However, because the cold-rolled steel sheets used in this study including the ECO-6 steel contained 0.5% Cu were isothermally treated at a low temperature of 430°C and for a shorter period of time of 3 min, it is hard to expect the precipitation strengthening of 9R or ϵ -Cu particles. Excellent tensile properties and formability of the ECO-6 steel must be derived from the combined effects of the solid solution strengthening arising from Cu solution in ferrite and the higher TRIP effect due to the increase in the retained austenite volume fraction. These results of the ECO-6 steel confirm the significance of the addition of Cu, a tramp element, in alloy designing in order to develop TRIP-aided steels with excellent mechanical properties.

The Cu-and-Ni-added ECO-8 steel shows slightly lower retained austenite stability, tensile elongation, and formability than the Cu-added ECO-6 steel, but has higher retained

austenite volume fraction and tensile strength. It shows superior uniaxial tensile properties and formability in comparison with the ECO-7 and ECO-9 steels. This is because Ni, a representative austenite stabilizer, is solved in austenite during intercritical annealing, stabilizes austenite, and consequently forms higher volume fraction of retained austenite during subsequent isothermal treatment. Although Cu addition leads to strengthening of ferrite grains, it has a shortcoming of possible occurrence of hot shortness during continuous casting or hot-rolling processes.^{8,9,32)} This hot shortness arises when the liquid phase of Cu concentrated at high temperatures infiltrates into austenite grain boundaries.¹¹⁾ In order to prevent this, Ni is added typically in the amount corresponding to 0.7 time of Cu addition.³³⁾ Since Ni can have the preventative effect of hot shortness in addition to increased retained austenite volume fraction, it can be usefully applied in combination with Cu to the development of low-carbon TRIP-aided cold-rolled steel sheets with excellent properties.

In the case of the Cr-containing ECO-7 and ECO-9 steels, strength visibly increases, whereas retained austenite volume fraction and elongation are dramatically reduced. They show the tensile behaviors similar to those of dual phase steels, much different from those of the ECO-6 and ECO-8 steels. As observed in Fig. 4, the microstructure is composed of dual phases of ferrite and martensite. According to the Fe–Cr binary phase diagram,³⁴⁾ a small amount of Cr addition, a representative ferrite stabilizer, as low as 0.4% can stabilize ferrite in the temperature range from 780 to 790°C. Consequently, ferrite formation proceeds actively in the intercritical annealing temperature range, and it is likely that austenite is further stabilized by diffusion of carbon atoms from ferrite to austenite. Under this situation, the ECO-7 and ECO-9 steels are supposed to show relatively high retained austenite volume fraction. However, their retained austenite volume fractions are below 10%, and their stabilities are much lower than that of the ECO-6 and ECO-8 steels. This can be explained as follows. When Cr is added, the stability of austenite formed during intercritical annealing might increase, but its hardenability also increases. This case can be observed in microalloying steels for hot forging, to which Cr is typically added in order to enhance the hardenability. Thus, when the cooling rate after the intercritical annealing is fast, most austenites are transformed to martensites to form dual phases of ferrite and martensite. In this process, a lot of carbon atoms are pinned inside martensite, and the volume fraction and stability of retained austenite decrease, since the amount of carbon atoms which can contribute to the formation of retained austenite during isothermal treatment is reduced. For this reason, the strengthening effect of dual phases overrides the TRIP effect, thereby resulting in extremely high tensile strength but poor elongation and formability. Considering that the values of LDH_0 and FLC_0 measured during the LDH test under no lubrication condition increase by 40–50%, the formability of the ECO-7 and ECO-9 steels can be evaluated to be relatively excellent, equal to that of high-formability cold-rolled steel sheets reported by Hiwatashi *et al.*¹⁾

5. Conclusions

In the present study, volume fraction and stability of retained austenite, mechanical properties, and formability were investigated for four kinds of low-carbon TRIP-aided cold-rolled steel sheets containing tramp elements such as Cu, Cr, and Ni, and the following conclusions were reached:

(1) Formability as well as tensile properties of the Cu- and Ni-containing cold-rolled steel sheets were greatly improved as the strain-induced transformation of retained austenite was actively sustained up to the high strain region because of high volume fraction and stability of retained austenite.

(2) The cold-rolled steel sheets to which Cr was added alone or in combination with Ni showed a dual phase structure, together with low volume fraction and stability of retained austenite resulting from a large amount of transformed martensite.

(3) When tramp elements such as Cu, Cr, and Ni known as harmful ones were positively applied, it was confirmed that low-carbon TRIP-aided cold-rolled steel sheets with mechanical properties suitable for various application purposes and excellent formability could be successfully fabricated.

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