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New Types of Steel Sheets for Automobile Weight Reduction

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Abstract:

As the regulation of automobile fuel consumption is expected to grow severer toward the year 2000, light-weight automobiles with improved fuel economy are being developed. An important component of the automobile weight is the weight of the body that is made up of steel sheet, and the development of new steel sheets with higher strength and better formability is essential for reducing the weight of automobiles. To meet these needs, Nippon Steel has been engaged in the development and commercialization of high-formability and high-strength steel sheets with new functions. In this paper, the relations between the strength properties required for body parts and the relevant material factors are described first. Then, the mechanical properties of new steel sheets, such as work-hardening and bake-hardening formable steel sheet, retained austenite steel sheet, copper-bearing IF steel sheet, dual phase steel sheet, are introduced.

1. Introduction

The regulation of automobile fuel consumption is expected to be strengthened further toward the year 2000 in order to reduce the emission of carbon dioxide (CO_2), a gas claimed to be responsible for the global warming phenomenon. World automobile manufacturers are working hard to develop lighter automobiles with better fuel economy. Japanese automakers are pushing ahead with the development of technology to attain the target weight reduction ratios of 10% and 20%, respectively, by the years 1995 and 2000.

Steel sheets will remain an important automobile body material for years to come, and the development of high-strength and high-formability steel sheets is essential for achieving car weight reductions. To meet this demand, Nippon Steel has been engaged in the development and commercialization of super-formable and high-strength steel sheets with a variety of new functions. The performance characteristics of those steel sheets developed for automobile weight reductions are described below.

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2. Development Concept of Steel Sheets for Automobile Weight Reduction

2.1 Properties required of weight-saving steel sheets

The automobile is composed of body, undercarriage, power train, and many other parts. A weight reduction in the automobile must be realized while ensuring the necessary function of each component part. **Table 1** shows the main material factors for securing the desired strength of each principal part assuming that the shape of each part is constant[1]. Stiffness, an important property for inner and outer panels, is determined by Young's modulus and sheet thickness. Dent resistance, which is emphasized for outer panels, depends on flow stress and sheet thickness. Crash strength, which is most important for reinforcement parts, is governed by Young's modulus, flow stress, and sheet thickness. **Table 2** shows the ratios of stiffness, dent resistance, crash strength, and weight reduction calculated on the assumption that Young's modulus of the steel is constant. For those parts for which stiffness is important, weight reduction cannot be

Table 1 Strength properties required of automotive parts and material factors

Part	Panel stiffness	Dent resistance	Crash strength
Exposed panel	◎	○	
Inner panel	◎		○
Reinforcement part			◎
Material factor	$E \cdot t^3$	$\sigma \cdot t^2$	$E^{0.4} \cdot \sigma^{0.6} \cdot t^{1.8}$

E: Young's modulus, t: sheet thickness, σ: flow stress (~ tensile strength)

Table 2 Calculated steel sheet properties required for specific weight reduction ratios

Strength property	Weight reduction ratio			
	0% (present)	10%	20%	40%
Panel stiffness	E	1.4E	1.9E	4.6E
Dent resistance	TS = 290 MPa	TS = 370 MPa	TS = 490 MPa	TS = 780 MPa
Crash strength	TS = 290 MPa	TS = 440 MPa	TS = 590 MPa	TS = 1360 MPa

achieved only by using high-strength steel sheet. The structure and geometry must also be changed for such parts. Dent resistance and crash strength can be markedly improved by using a high-strength steel sheet.

Generally raising material strength results in lowering formability. Any attempt at a weight reduction by way of steel strength enhancement will be meaningless if it is to sacrifice formability. It is important to raise the strength of steel sheet while minimizing the loss of formability. Gage reduction further worsens formability. This loss of formability must be compensated for by adding extra formability to the reinforced steel sheet in some way or another. This means that the automobile weight reduction essentially requires the development of a novel steel sheet reinforcement or formability enhancement mechanism and its application in commercial steel sheet manufacture.

2.2 Directions of material development

The development of weight-saving steel sheets is carried out with full attention given to the intended strength and formability characteristics of automobile parts as described below.

The body accounts for so large a proportion of the automobile weight that top priority is given to the strengthening of both exposed and inner panels. Current rephosphorized steel sheet is limited to a maximum tensile strength of 340 MPa by its difficulty of forming. A high-formability and hi-bake-hardenability steel sheet with n value, r value and yield point close to those of conventional steel sheet and with flow stress after bake-hardening comparable to that of 390 to 440 MPa steel sheet is effective in achieving a weight saving of 5 to 10%. For a weight saving of 10 to 20%, new types of steel sheet with a tensile strength of 490 to 590 MPa and very high work hardening characteristics are earnestly looked for, assuming that panel stiffness is increased by improving the steel structure. The weight of body parts can be reduced by employing one-piece forming. One-piece panel forming requires a steel sheet of much higher formability than the conventional extra-deep drawing quality (EDDQ) steel sheet.

Among undercarriage parts, suspension parts require high material strength and durability, and this endorses the effectiveness of using high-strength steel sheet. A weight saving of 10% or more can be expected from the use of steel sheet with a tensile strength of 590 MPa or more. The suspension parts are complicated in shape and are characteristic in that they are formed by stretch-flanging. Steel sheet with a high hole expansion ratio is suited for this forming method. Wheel discs need high fatigue strength and are formed by severe stretching. Steel sheet with a tensile strength of 590 MPa or more and high stretchability is suited to this application. For wheel rims, high-formability, precipitation-hardening steel with a tensile strength of 590 to 780 MPa is most advantageous from the standpoint of flash butt weldability.

Reinforcement parts that need crash strength can reap the greatest benefit from the use of high-strength steel. Ultrahigh-strength steel sheet with a tensile strength of 980 MPa or more is necessary to achieve a sizable weight saving. Most reinforcement parts are relatively easy to form. High ductility and improved bendability are desired to expand the scope of application.

Many power train parts are still made from forging or machined from bar steel, but conversion to press forming is in progress for the purposes of weight reduction and productivity gain. Heat treatment hardening steel that is high in ductility during press forming and develops high tensile strength through heat treatment is best suited for press-formed power train parts.

Material properties required from a formability point of view have been described above. Generally, increasing strength lowers weldability and platability. Material development efforts must take these possibilities into account.

The development and performance characteristics of new types of steel sheets useful for automobile weight reduction are introduced below.

3. High-Formability Steel Sheet

Ever higher formability is demanded of steel sheet for panels. A steel grade, called super extradeep drawing quality (Super EDDQ), was developed to meet the demand[2]. As shown in **Fig. 1**, the super EDDQ grade has forming properties that are much better than those of the EDDQ grade. The r value is 2.5, the total elongation exceeds 55%, and the n value is above 0.27. The super EDDQ grade is useful as steel sheet for one-piece forming of panels and similar body parts.

The carbon content is reduced to about 10 ppm to enhance formability; Then, titanium is added singly or in combination with niobium to produce the super EDDQ grade as interstitial-free (IF) steel. The IF steel is continuously annealed at high temperatures. This heat treatment can not only improve the properties of, but also impart bake hardenability to the IF steel as required.

4. Low-Yield Point, High-Strength Steel Sheet

High-strength steel sheet for exposed panels must have a high

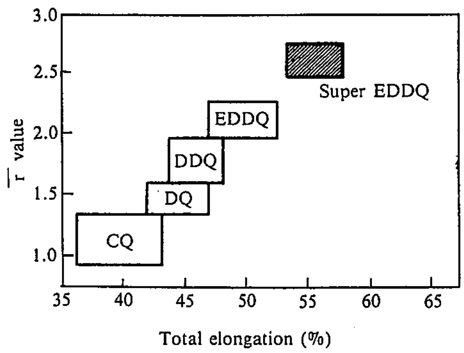


Fig. 1 Grades and mechanical properties of cold rolled steel sheets

r value and a low yield point. It is empirically known that yield point must be limited to 240 MPa or less in order to prevent surface unevenness in exposed panels. Rephosphorized steel sheet has an r value of about 1.6 and is widely used, except for deep-drawn parts like fenders. The yield point of rephosphorized steel sheet is 240 MPa or less when its tensile strength is about 340 MPa or less. The maximum tensile strength at which the rephosphorized steel sheet can be used to form panels is said to be 340 MPa.

High-strength IF steel sheet with the addition of such elements as manganese and chromium that do not raise the yield point for the amount of their addition is lower in the yield point than conventional steel sheets, as shown in **Fig. 2**. The yield point can be lowered to 240 MPa or less if tensile strength is 440 MPa. The work hardenability (WH) of the high-strength IF steel sheet is very high at about 60 MPa. It can also be provided with a bake hardenability of about 40 MPa.

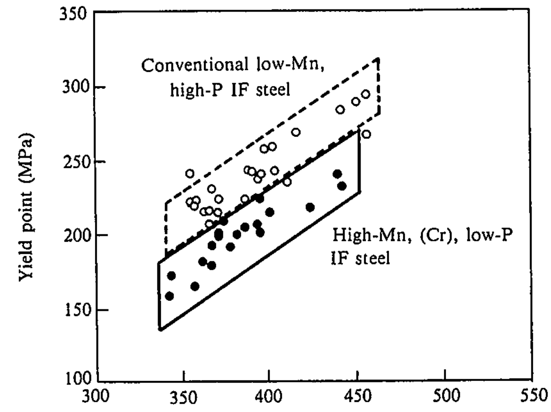


Fig. 2 Relationship between tensile strength and yield point of low-yield point, high-strength IF steel sheet

5. Retained Austenite Steel Sheet

5.1 Cold rolled retained austenite steel sheet

When C-Si-Mn steel is hot rolled, cold rolled, and then controlled as to microstructure by two-stage annealing in a continuous annealing furnace, several to about 20% of the austenite structure is retained. The retained austenite microstructure transforms into hard martensite during plastic deformation, remarkably enhancing the ductility of the obtained sheet[3]. This is called transformation-induced plasticity (TRIP), and the high-ductility steel sheet manufactured by utilizing the TRIP phenomenon is retained austenite steel sheet.

The amount of retained austenite (γ_R) and strength of the retained austenite steel sheet changes with the carbon content, as shown in **Fig. 3**. The ductility provided by the retained austenite is very high. As shown in **Fig. 4** and **Photo 1**, 590-MPa retained austenite steel sheet exhibits stretchability that is superior to that of 440-MPa rephosphorized steel sheet. Study is under way to apply this steel sheet to automotive parts. Its microstructure is as shown in **Photo 2**.

5.2 Hot rolled retained austenite steel sheet

The retained austenite steel sheet is produced also as hot rolled steel sheet[4], through the control of chemical composition and by controlling thermal hysteresis during the continuous hot roll-

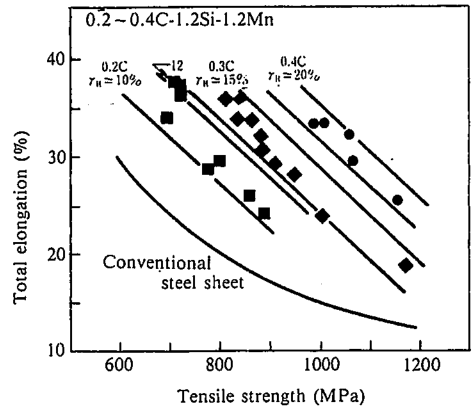


Fig. 3 Effect of retained austenite content on tensile strength and total elongation of retained austenite steel sheet

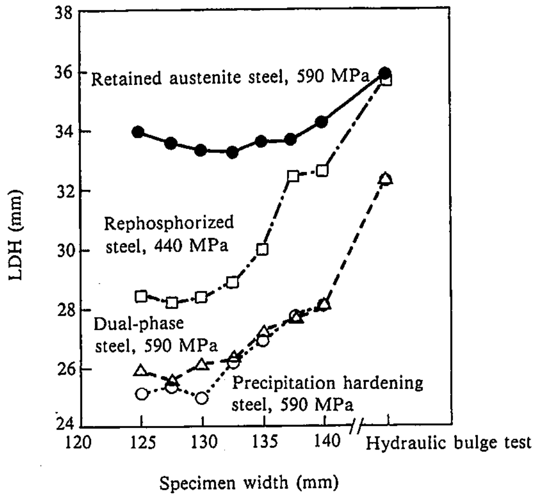


Fig. 4 Limiting dome height (LDH) of steel sheet in LDH test

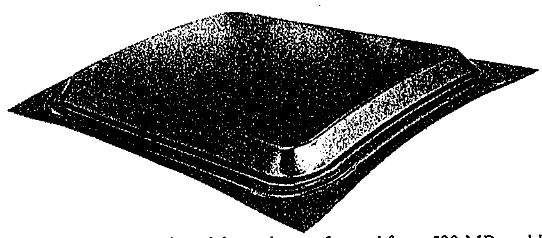


Photo 1 Appearance of model panel press formed from 590-MPa cold rolled retained austenite high-strength steel sheet

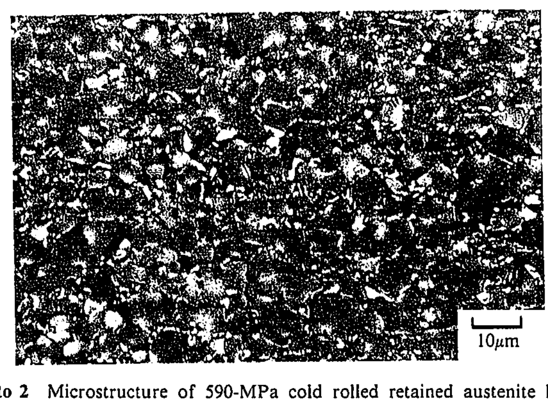


Photo 2 Microstructure of 590-MPa cold rolled retained austenite high-strength steel sheet (blue: ferrite, brown: bainite, white: austenite)

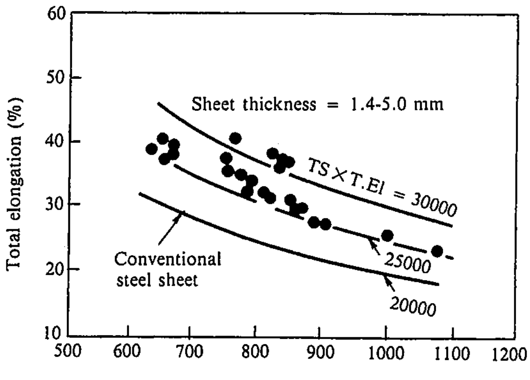


Fig. 5 Relationship between tensile strength and total elongation of hot rolled retained austenite high-strength steel sheet

ing process. **Fig. 5** shows the relationship between the tensile strength and ductility (total elongation) of the retained austenite steel sheet. As evident from the figure, ductility in the tensile strength range of 590 to 980 MPa is higher than obtainable with the conventional steel. By virtue of this high formability, the hot rolled retained austenite steel sheet is finding many new applications.

6. Heat Treatment-Hardening Steel sheet

Bake-hardening steel sheet is mild during press forming and is hardened through paint baking. The bake hardenability of this type of steel is limited to a range of about 30 to 50 MPa to suppress the return of yield-point elongation at room temperature.

When sheet is hot rolled from ultralow-carbon steel with a supersaturated solid solution of about 1.5% copper, it exhibits excellent formability and a very high heat treatment hardenability of about 150 to 200 MPa, as shown in **Fig. 6**[5]. The heat treatment hardening steel sheet can be formed as severely as 390-MPa IF steel sheet before heat treatment and strengthened to 590 MPa after heat treatment at 500 to 700°C for several minutes. The tensile strength range of conventional deep-drawing quality high-strength cold rolled steel sheet is 440 MPa downward. Previously no methods were available for imparting deep drawability to steel sheet of 490 MPa or higher in tensile strength. In the new process, IF steel with solid solution of copper is hot rolled, and then is continuously annealed to achieve recrystallization and obtain a high r value. Subsequent copper-precipitation heat treatment provides an r value of about 1.9 at 590 MPa, as shown in **Table 3**[6,7].

The size of copper precipitates that enhance the steel strength is extremely small at about 3 nm. An AP-FIM image of copper precipitates is given in **Photo 3**[7].

7. High-Flangeability Steel Sheet

Undercarriage parts are formed often by severe flanging. These automotive parts therefore require a steel sheet with high strength and high stretch flangeability. The stretch flangeability of steel sheet is greatly affected by the shapes of nonmetallic inclusions and carbides.

Bainite steel sheet with carbides finely dispersed by controlling the thermal hysteresis of C-Si-Mn steel after hot rolling features a high hole expansion ratio of 2.0 or more at the tensile strength of 590 MPa, as shown in **Fig. 7**[8,9]. The hole expansion

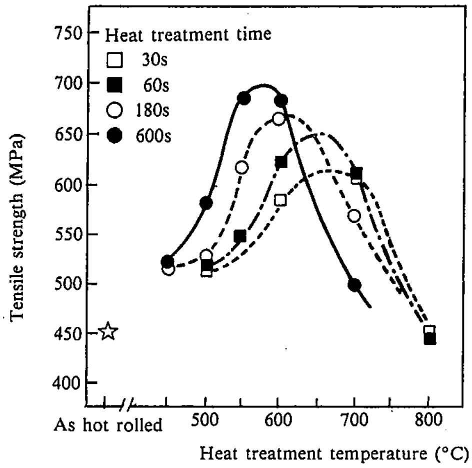


Fig. 6 Effects of heat treatment conditions on tensile strength of 1.6% copper IF hot rolled steel sheet

Table 3 Mechanical properties of cold rolled steel sheet (thickness: 0.8 mm)

Steel	Yield point (MPa)	Tensile strength (MPa)	Total elongation (%)	$\bar{r}$ value
Copper-bearing IF steel	507	610	24.4	1.90
Conventional 590-MPa steel	429	610	23.9	1.10
Conventional 370-MPa steelt	236	403	37.6	1.54

Photo 3 FIM image of copper precipitate in 1.6%Cu IF steel heat treated at 550°C for 600 s

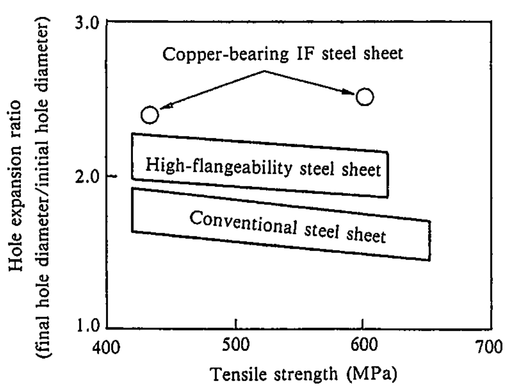


Fig. 7 Hole expansion ratio of high-strength steel sheet

ratio is very high at 2.5 in the 590-MPa copper-bearing IF hot rolled steel sheet, which has copper precipitated during coiling after hot rolling. These steels are very useful as materials of high-flangeability sheets.

8. Dual Phase High-Strength Steel Sheet

When Si-Mn steel sheet held in the ferrite-plus-austenite two-phase region is quenched in the hot rolling stage or in the continuous annealing stage after cold rolling, a dual-phase microstructure of soft ferrite and hard martensite is obtained. This steel sheet features not only a high tensile strength of 590 MPa or more, but also a high n value, ductility and fatigue strength. It is used to make wheels and other automotive parts that require high stretchability and fatigue strength.

Fig. 8 shows the fatigue behaviors of 590-MPa niobium-microalloyed precipitation-hardening steel sheet (steel A) and dual-phase high-strength steel sheet (steel B)[10]. Steel A exhibits monotonic cyclic softening behavior. Steel B hardens in the initial stage and softens only to a small degree thereafter. Steel B consequently has high resistance to critical fatigue cracks.

These phenomena are reflected in the difference of dislocation arrangement in the fatigue process, as shown in **Photo 4**. In steel A, subgrain formation readily proceeds to facilitate the dislocation arrangement that is stable from the point of view of energy. In steel B, in contrast, cell structures develop in ferrite grains, and are maintained through the subsequent softening process.

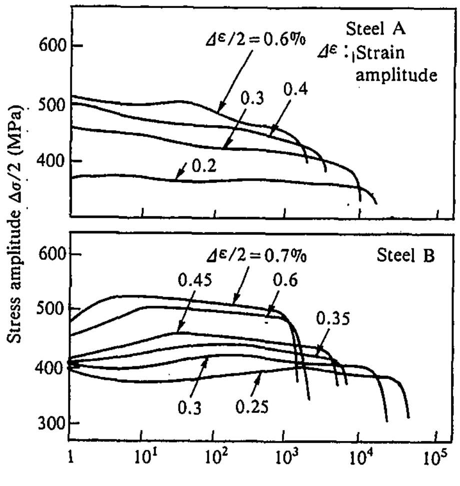
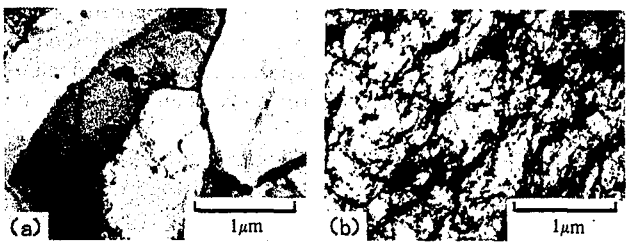


Fig. 8 Stress response curves of niobium-microalloyed precipitation-hardening high-strength steel sheet (steel A) and dual phase high-strength steel sheet (steel B) in low-cycle fatigue test



(a) Niobium-microalloyed precipitation-hardening high-strength steel sheet (steel A)
(b) Dual phase high-strength steel sheet (steel B)

Photo 4 Electron micrographs of steel sheet specimens in fatigue test ($N = 4 \times 10^3$, $\Delta\varepsilon/2 = 0.3\%$)

9. Ultrahigh-Strength Steel Sheet for Reinforcement Parts

This type of steel utilizes the transformation phase hardening and precipitation hardening mechanisms, and is processed by continuous annealing to a tensile strength of 980 MPa or more. Good bendability is often required of reinforcement parts. Grain refinement and uniform microstructure are important factors in the enhancement of bendability. Special attention is given to the steel chemistry and the thermal histroy in the continuous annealing process.

10. Conclusions

Material properties required to reduce the weight of automobiles and new types of steel sheet developed to meet this requirement have been introduced above. Descriptions have been made mainly in terms of necessary mechanical properties. However the growing trends toward the use of coated steel sheets in automobiles points to the need for focusing attention on coating adhesion, formability and weldability in the development of new steel sheets.

Although it is difficult to reconcile social responsibility for global warming and other environmental problems with needs from automobile users, we will have to pursue the ultimate in technology under close coordination among the design, material, and fabrication personnel to continue to create automobiles that meet the needs of users.

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