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Development of Bake-Hardening High-Strength Cold-Rolled Sheet Steels for Automobile Exposed Panels

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Development of Bake-Hardening High-Strength Cold-Rolled Sheet Steels for Automobile Exposed Panels*

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Synopsis:

New cold-rolled sheet steels (including those coated) with excellent formability and high bake-hardenability suitable for thinner-gage automobile exposed panels were investigated. (1) High-temperature annealing above 850°C and subsequent rapid cooling of a Nb-bearing extra-low C steel (Nb(at%)/C(at%)~1.0) provided an intense {111} recrystallization texture favorable for deep drawability and some amount of solute C effective for bake-hardenability. (2) This processing principle was applied to develop extra-deep drawing cold-rolled sheet steels with bake-hardenability by using newly developed continuous annealing lines (KM-CAL) capable of high-temperature annealing at approximately 900°C. (3) Organic composite-coated sheet steels with similar mechanical properties were developed by applying a new organic film baked at a low temperature to the continuously annealed sheet steels. (4) Hot-dip galvannealed sheet steels with extra-deep drawability and bake-hardenability were also developed by using newly installed continuous hot-dip galvanizing lines capable of high-temperature annealing and rapid cooling. (5) These new sheet steels are suitable for thin-gage automotive outer panels such as fenders.

1 Introduction

Specific properties are required for cold-rolled sheet steels (including those coated sheets), especially for automobile exposed panels. One of the strongest demands is for a high-strength sheet steel of thinner gage to reduce a car's weight, which will lower the volume of exhausted CO_2 gas and the fuel consumption. On the other hand, automobile panels press-formed from sheet steel have become larger and complicated. This integration of press-formed parts demands higher press-formability than that of conventional sheet steels. Surface-coated sheet steels are also increasingly required to improve automobile life. To summarize these requirements, a high-strength steel with good press-formability that is suitable for coating is strongly requested for automobile exposed panels.

It is difficult to avoid a deterioration of coating properties (especially with hot-dip galvanized products) and/or of formability (particularly ductility) when a relatively large amount of alloying elements is added to provide required strength of sheet steels. In the case of a bake-hardening, high-strength steel, a lower content of alloying elements is necessary since it utilizes strain age-hardening. **Figure 1** represents the mechanism for strain age-hardening and the measuring method for bake-hardenability (BH) in a tensile test. A sheet steel containing a small amount of solute C (approximately 0.001%) exhibits a low yield strength (YS) as received before press-forming. After press-forming by plastic deformation, the induced dislocations result in work-hardening of the sheet steel. Car bodies are bake-painted after

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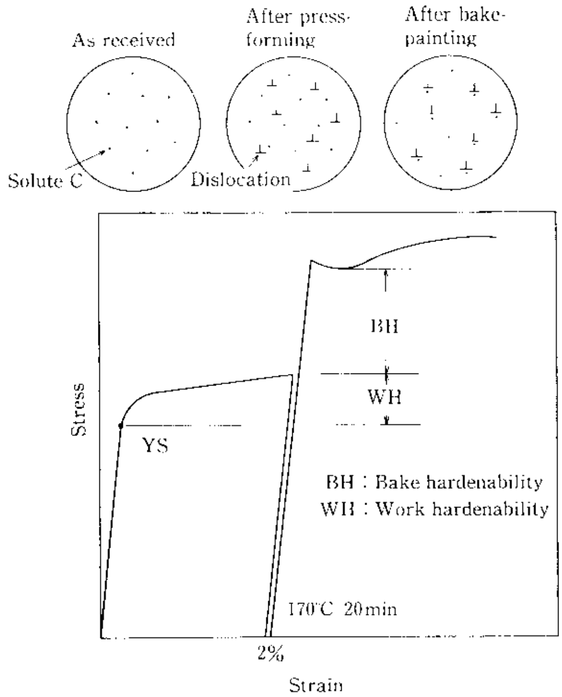

Fig. 1 Schematic illustration showing mechanism of strain age-hardening and measuring method of bake-hardenability (BH) in tensile test

press-forming and assembling, the press-formed parts being heated at approximately 170°C during the bake-painting process. After this process, the dislocations induced by press-forming are stabilized by solute C diffusing adjacent to the core of a dislocation. A higher stress is required to promote the slip movement that occurs with plastic deformation of the stabilized dislocations when an external stress is applied to press-formed and bake-painted parts. Thus, a bakehardenable sheet steel exhibits a low yield strength before press-forming, and a high yield strength in a completed car after bake-painting. However, the presence of a small amount of solute C (approximately 0.001%) during the annealing process markedly deteriorates the press-formability, especially the drawability, of sheet steels.

This paper describes the processing principle for a bake-hardening and extra-deep drawing sheet steel[1,2] and its application to cold-rolled and surface-coated products.

2 Processing Principle

Drawability is governed by the crystal orientation of a sheet steel. The higher the {111} intensity normal to the sheet steel surface, the better is the drawability of ordinary polycrystal sheet steels. This drawability is evaluated by the Lankford-value (r-value) from a tensile test. A higher r-value is advantageous for deep drawability, and the r-value for extra-deep drawing grade (EDDQ) material generally exceeds 2.0.

For conventional bake-hardening, cold-rolled sheet steels with r-values of less than 2.0, the following two manufacturing methods are known. The first one involves the continuous annealing process with low-C Al-killed steels (C = 0.02-0.06%).[3,4]The steels are coiled at a high temperature after hot-rolling, which coarsens the carbides and stabilizes N as AlN. Subsequent cold-rolling and continuous annealing results in an intense {111} recrystallization texture. Sheet steels with r-values of 1.5 to 1.7 can be produced by this method. Such continuously annealed sheet steels contain a large amount of solute C just after heating and soaking, since part of the carbides dissolves during recrystallization annealing. Over-aging during cooling stabilizes solute C as Fe_3C again. An adequate amount of solute C (approximately 0.001%) available for bake-hardenability is obtained by controlling the over-aging conditions. A higher content of solute C than 0.001% results in deteriorated ductility and anti-aging characteristics.

The second conventional method involves a box annealing process with extra-low-C Al-killed steel (C = 0.005-0.010%) which is low-temperature coiled at hot rolling.[5] The ordinary slow-heating box-annealing process makes it possible to produce sheet steels with r-values of 1.7-1.9. An adequate amount of solute C can be retained after annealing since the precipitation of Fe_3C is retarded by cooling due to the low supersaturation of C.

The above-mentioned conventional methods have the following disadvantages:

(1) It is difficult to obtain extra-deep drawability with the r-value of over 2.0 required.

(2) The first method is impossible to carry out on an ordinary continuous galvanizing line with no over-aging section.

The second method indispensably requires double-annealing to manufacture hot-dip galvanized products, since it presupposes the box annealing process. Thus, it is very difficult to produce a sheet steel with both bake-hardenability and extra-deep drawability by these conventional methods. Furthermore, the conventional methods are not suitable for producing coated products such as hot-dip galvanized sheet steels.

One way to obtain extra-deep drawability is by stabilizing C in a sheet steel as TiC[6] or NbC.[7,8] However, this type of steel exhibits little bake-hardenability under ordinary annealing conditions. **Figure 2** shows the r-value and BH of Ti- and Nb-added cold-rolled sheet steels as a function of the soaking temperature during continuous-type annealing. In the case of the atomic ratios of Nb/C and Ti*/C being less than 0.4, high BH can be obtained. However, the r-value in such a case is very low due to the presence of a large amount of solute C at the beginning of recrystallization. Ti* is defined in this paper as the content of Ti after subtracting the Ti amount combined with N and S from the

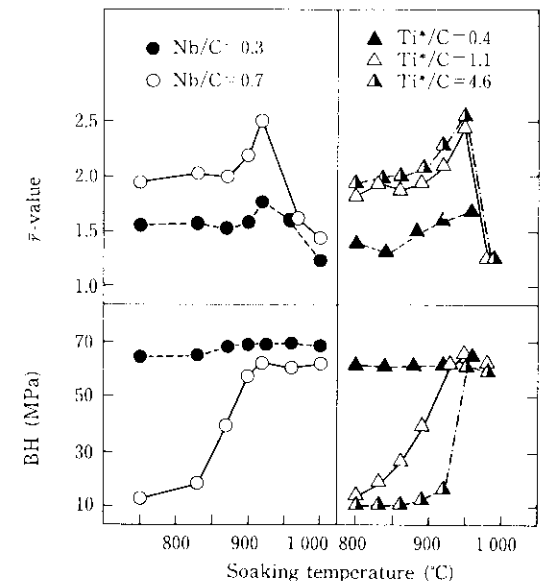

Fig. 2 Effect of soaking temperature on r-value and BH in cold-rolled Nb- and Ti-added extra-low C steels

total Ti content. Soaking at higher than 850°C yields both a high r-value and high BH when the atomic ratio of the alloying element to C is approximately unity. It is difficult to obtain high BH even at high temperatures over 850°C in the case of a higher Ti*/C ratio.

The mechanism for this phenomenon and the application to product development are schematically illustrated in **Fig. 3**, the basic material being an extra-low-C Al-killed steel. A strong carbide-former is added to stabilize C, Ti and Nb being suitable under practical conditions. The content of Ti and Nb needs to be strictly controlled against the C content as illustrated in Fig. 2. Since Ti preferentially combines with N and subsequently stabilizes S in contrast with Nb, it is difficult to practically adjust an adequate amount of Ti to suit the C content. Furthermore, a Nb-bearing steel is more advantageous to obtain good coating properties for hot-dip galvanized products when compared with a Ti-bearing steel. Thus, Nb was used for commercial production.

Nb-added extra-low-C steel with approximately unity for the Nb/C atomic ratio was first processed by hot rolling and coiling at a temperature higher than 600°C, resulting in the stabilization of almost all C and N as NbC and AlN, respectively. After cold rolling and heating above the recrystallization temperature (approximately 750°C), an intense {111} recrystallization texture had developed. NbC and AlN are stable during heat treatment up to the recrystallization temperature. Further heating to above 850°C results in the dissolution of NbC, as a result of some amount of solute C. At this stage, the influence of solute C on the texture development might be negligible, since this stage corresponds to the growth of recrystallized grains. On the other hand, AlN dissolves little during high-temperature soaking from 830°C to 900°C.[1)] It was possible to retain a small amount of solute C by subsequent rapid cooling so as not to precipitate it again.[2)] According to the foregoing principle, a sheet steel having both bake-hardenability and extra-deep drawability can be produced.

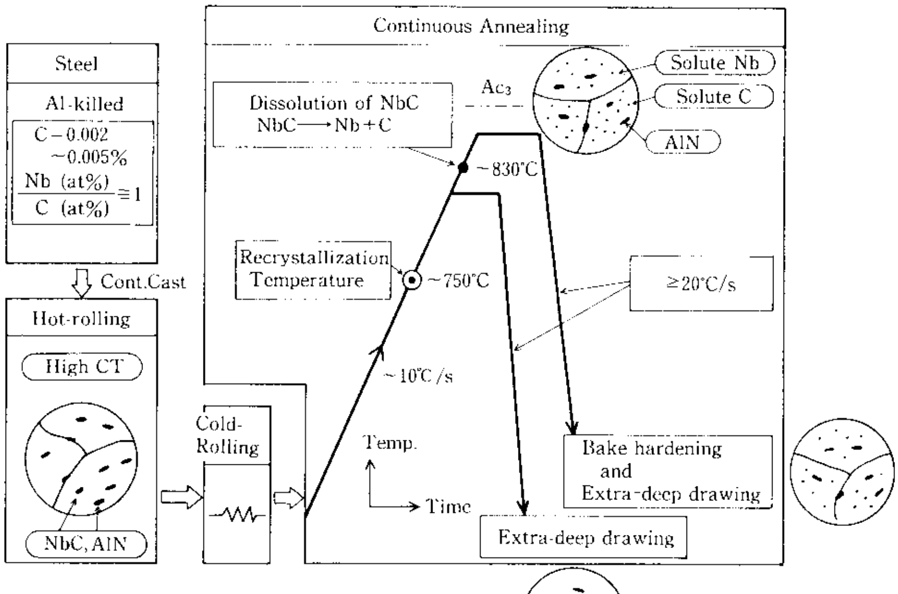

Fig. 3 Processing principle of bake-hardening and extra-deep drawing sheet steel

3 Processing Conditions and Mechanical Properties of Bake-Hardening Cold-Rolled Sheet Steel

There were many aspects to be resolved for the commercial production of bake-hardening cold-rolled sheet steels based on the above-mentioned processing principle. In panticular, many advanced techniques were developed for the steelmaking[9,10] and continuous annealing[11,12] technology that was required. In this section, the processing conditions and the mechanical properties of bake-hardening cold-rolled sheet steels will be described.

Slabs (C ≅ 0.002%, Nb(at%)/C(at%) = 0.35-1.4) were produced by a process consisting of steelmaking with a converter, RH degassing, and continuous casting. The other elements were kept almost constant at 0.1-0.2%Mn, P ≦ 0.02%, S ≦ 0.01%, N ≦ 0.003%, and Al ≦ 0.04%. These slabs were hot-rolled and coiled at approximately 680°C. The hot strips were cold-rolled to 0.7 mm in thickness (75% cold-rolling reduction), annealed at 880°C on the continuous annealing line, and then cooled at approximately 40°C/s. **Figure 4** shows the relationship between the mechanical properties and the atomic ratio of Nb to C. BH was almost constant at nearly 40 MPa throughout the range of Nb/C ratio used in this experiment. The optimum Nb/C value was from 0.5 to 1.2, judging from the *r*-value and the total elongation (El). The tensile strength (TS) of these sheet steels was 300 MPa, although higher TS grades than this can be manufactured by adding solution-hardening elements

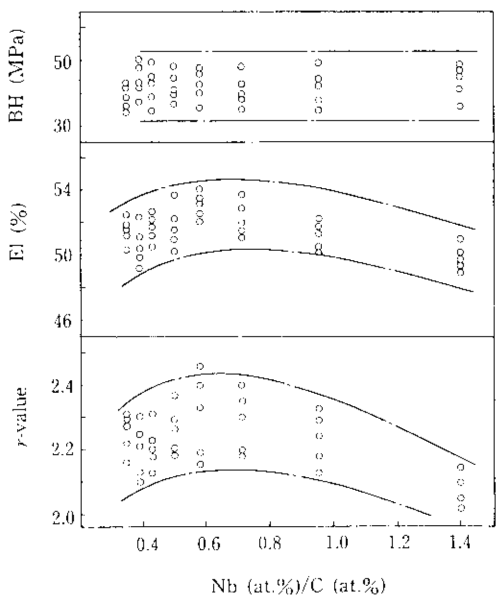

Fig. 4 Relation between mechanical properties and atomic ratio of Nb to C in continuously annealed sheet steels (C ~ 0.002%, soaking temperature 880°C, steel thickness 0.7 mm)

Table 1 Typical mechanical properties of continuously annealed cold-rolled sheet steels with extra-deep drawability and bake-hardenability

TS grade (MPa)	YS (MPa)	TS (MPa)	El (%)	$\bar{r}$	BH (MPa)
300	172	307	51	2.2	43
350	197	352	43	2.1	45

Thickness: 0.7 mm

such as P to the steel chemistry.

The typical mechanical properties of bake-hardening high-strength sheet steels commercially produced are presented in **Table 1**. Both sheet steel grades of 300 MPa and 350 MPa TSs exhibit extra-deep drawability (*r*-value of over 2.0) and high bake-hardenability (BH of 40 MPa).

4 Processing Conditions and Mechanical Properties of Bake-Hardening High-Strength Surface-Coated Sheet Steels

Hot-dip galvannealed and organic composite-coated products will be described for surface-coated sheet steels in this section.

The normal hot-dip galvanizing process consists of recrystallization annealing and subsequent coating on one line, the annealing process being similar to that used for the continuous annealing of the cold-rolled products. A processing method similar to that for the cold-rolled bake-hardening products by continuous annealing can be applied to manufacture hot-dip galvanized bake-hardening products. Hot-dip galvanized sheet steels are reheated to approximately 500°C for galvannealing in the case of the galvannealed products. The effect of galvannealing temperature on the mechanical properties was investigated. **Figure 5** illustrates the rela-

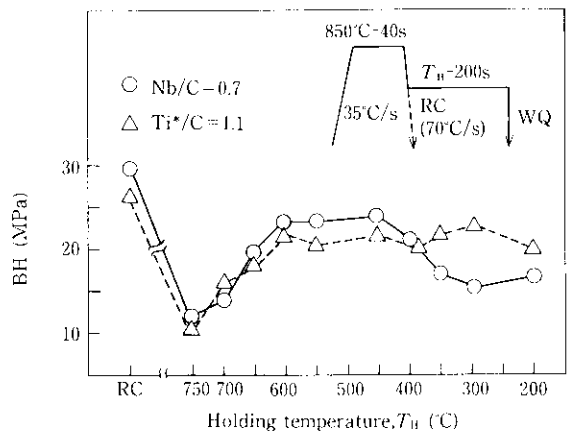

Fig. 5 Effect of holding temperature on BH of rapidly cooled sheet steels after soaked at 850°C

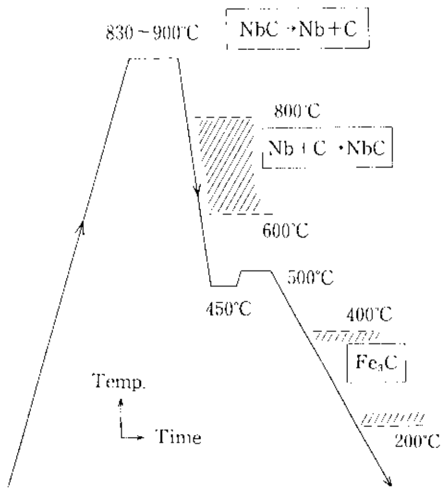

Fig. 6 Schematic illustration showing typical heat cycle of hot-dip galvannealing for extra-deep drawing and bake-hardening sheet steels

tionship between the holding temperature after annealing at 850°C, during which a part of the carbides dissolves, and BH of steels with approximately unity for the Nb/C and Ti*/C atomic ratios. A large decrease of BH was found from holding at nearly 750°C due to the reprecipitation of Ti- or Nb-carbides.[2] A smaller decrease of BH was detected from holding at close to 300°C due to the precipitation of Fe-carbides.[1] The decrease of BH from holding at between 400°C to 600°C was small, so the influence on BH of galvannealing at approximately 500°C might be negligible.

The heat cycle for producing galvannealed products is schematically illustrated in **Fig. 6**. The high-temperature annealing process on a continuous hot-dip galvanizing line for the Nb-bearing extra-low-C cold-rolled sheet steel yields some solute C due to NbC dissolution, so the sheet steel is rapidly cooled to avoid reprecipitation of NbC in the temperature range up to 600°C. After hot-dip galvanizing, the coated sheet steel is galvannealed at about 500°C, this process having little affect on the amount of solute C for BH. Subsequent rapid cooling at between 400°C and 200°C avoids the precipitation of Fe-carbides. The typical mechanical properties of bake-hardening high-strength galvannealed sheet steel manufactured by the above-mentioned process are shown in **Table 2**.

To next product to be described is a bake-hardening organic composite-coated sheet steel, **Fig. 7** showing a typical cross-sectional configuration of the newly developed organic composite coating. The layer close to base steel is an electrodeposited Zn-Ni alloy coating. Almost no change in the mechanical properties of the bake-hardening sheet steels after the electrodeposited coating occurred, since the temperature for the coating process is below 100°C. To produce the organic film coating as the top layer, however, the conventional process requires heating to temperatures higher than 250°C. **Figure 8** shows the mechanical properties of a bake-hardening cold-rolled sheet steel after the materials had been heated to simulate the organic film coating process. The materials are cold-rolled and continuous-annealed sheet steels of 350 MPa TS grade. Heating above 150°C caused an increase in yield elongation (YEl) and yield strength (YS), resulting in a deterioration in press-formability. This phenomenon might have resulted from C diffusion into the dislocations induced

Table 2 Mechanical properties of surface-coated cold-rolled sheet steels with extra-deep drawability and bake-hardenability

Steel	YS (MPa)	TS (MPa)	El (%)	$\bar{r}$	BH (MPa)
Hot-dip galvannealed	208	357	41	1.9	42
Organic composite coated	196	353	42	2.0	39

Steel thickness: 0.7 mm

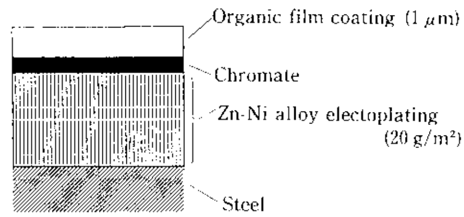

Fig. 7 Cross-sectional configuration of newly developed organic composite coating

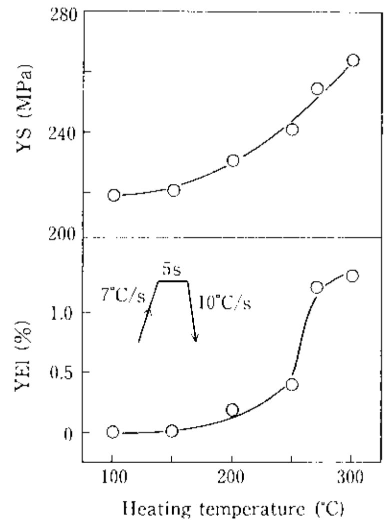

Fig. 8 Mechanical properties of bake-hardening sheet steel as a function of heating temperature at organic film baking

by temper-rolling after continuous annealing. In other words, the sheet steel hardened during the coating process before press-forming. A new organic film with a heating temperature of approximately 150°C was developed to avoid this deterioration of mechanical properties,[13] and the typical mechanical properties of this bake-hardening organic composite-coated sheet steel are presented in Table 2. The coated sheet steel possesses both extra-deep drawability and bake-hardenability equivalent to the galvannealed sheet steel. Other coating systems can be applied to this type of sheet steel as long as the coating process has no adverse effects on the mechanical properties including BH.

5 Strain Aging Behavior and Application to Automobile Parts

The newly developed bake-hardening high-strength sheet steels contain solute C of approximately 0.001%. This solute C easily diffuses in a steel, even at ambient temperature. Consequently, bake-hardening sheet steels containing solute C might suffer from a deterioration of mechanical properties due to aging before press-forming by vehicle producers. **Figure 9** shows the change of mechanical properties of the bake-hardening sheet steel (BH of 40 MPa) due to aging at 30°C, ΔYS and ΔEl denoting the change of YS and El, respectively, after aging. No distinct change was apparent within 90 days (3 months) after aging at 30°C. On the other hand, N can also be utilized for bake-hardenability. However, the diffusion of N in a steel is faster than that of C, as a result of the rapid deterioration of mechanical properties due to aging of a sheet steel containing solute N.[14] With the newly developed bake-hardening sheet steels, solute C mainly remains instead of solute N.

Bake-painting is often performed at about 170°C, although this baking temperature is being decreased to save energy. The baking time for the simulation of bake-painting was 20 min in a tensile test for BH. The actual manufacturing process for painting includes two or more coats, so that the total time for baking reaches 30 min or longer. **Figure 10** demonstrates the flow stress increment due to strain-aging in the bake-hardening sheet steel (BH of 40 MPa) as a function of the heating temperature and time in the simulated bake-painting process. The pre-strain was a 2% stretch. The flow stress increment induced by strain-aging decreases slightly with decreasing baking temperature. However, a high increment in the flow stress can be maintained even at 140°C when the sheet steel is bake-painted for 40 min, which is close to the total time of the actual process.

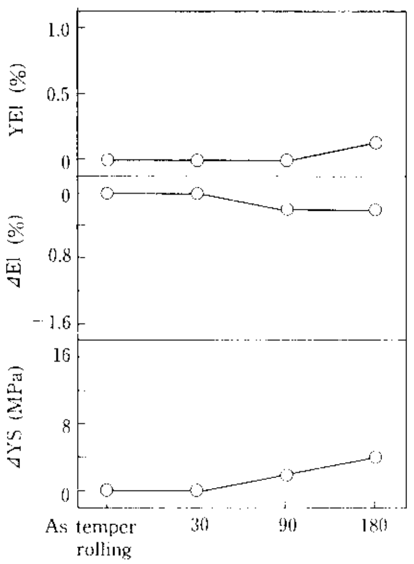

Fig. 9 Change of mechanical properties of bake-hardening sheet steel due to aging at 30°C

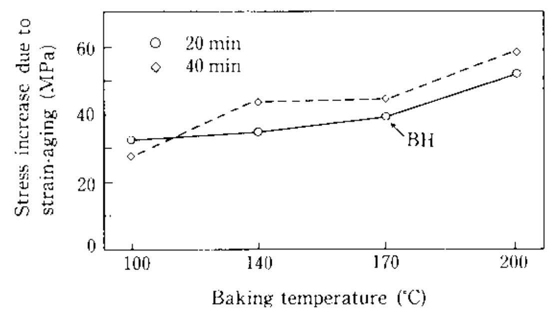

Fig. 10 Stress increment due to strain-aging in bake-hardening sheet steel plotted against heating temperature at bake-painting (pre-strain in stretch: 2%)

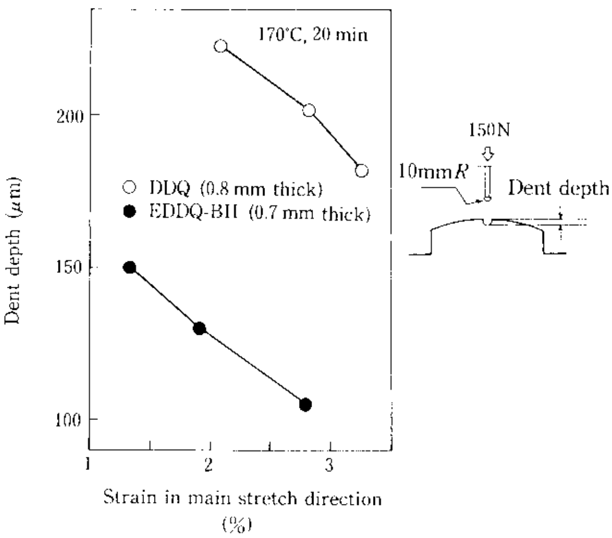

Fig. 11 Dent resistance of bake-hardenable extra-deep drawing quality high strength sheet steel (EDDQ-HSS, 0.7 mm thick) compared with deep drawing quality mild steel (DDQ, 0.8 mm thick)

Vehicle producers are thus able to decrease the bake-painting temperature and maintain a high increment in the the flow stress in press-formed and bake-painted parts.

Resistance to denting is required of exposed panels such as outer door skins when the gage is decreased to reduce the car weight. The dent resistance of a press-formed sheet steel is proportional to its yield strength[15] as well as to its thickness. The bake-hardening sheet steel provides high dent resistance in the thinner gages due to high increment of flow stress after press-forming and bake-painting. The dent resistance of the newly developed sheet steels is presented in **Fig. 11**, the material being a bake-hardening cold-rolled sheet (350 MPa TS grade, 0.7 mm thickness). The comparison material is a non-bake-hardening mild sheet steel (0.8 mm thickness). The strain in the main stretch direction was varied by changing the blank holding force during press-forming to the degree shown in Fig. 11.[16] The press-formed samples were then promptly heated at 170°C for 20 min to simulate the bake-painting process, the residual dent depth in the center after loading being measured in the manner described in Fig. 11. The dent resistance of bake-hardening high-strength sheet steel was better than that of a non-BH sheet steel in a thicker gage.

Photos 1 and **2** show press-formed samples of the newly developed bake-hardening sheet steels, the for-

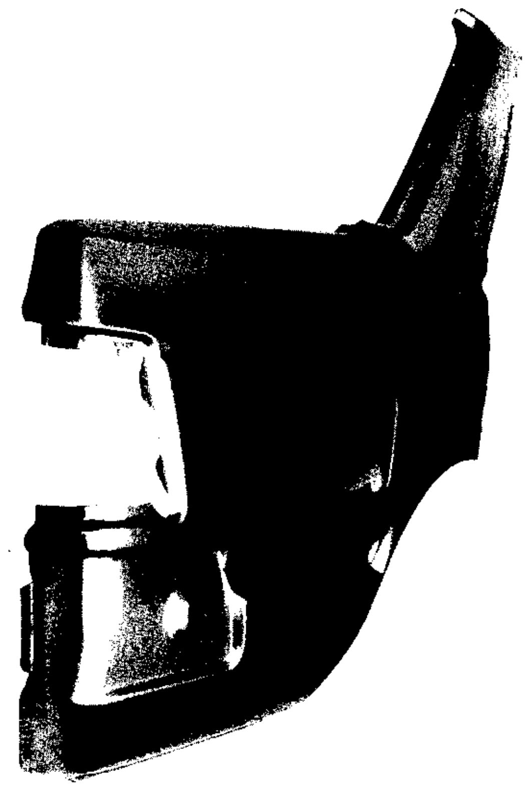

Photo 1 Rear fender panel press-formed by extra-deep drawing and bake-hardening cold-rolled sheet steel

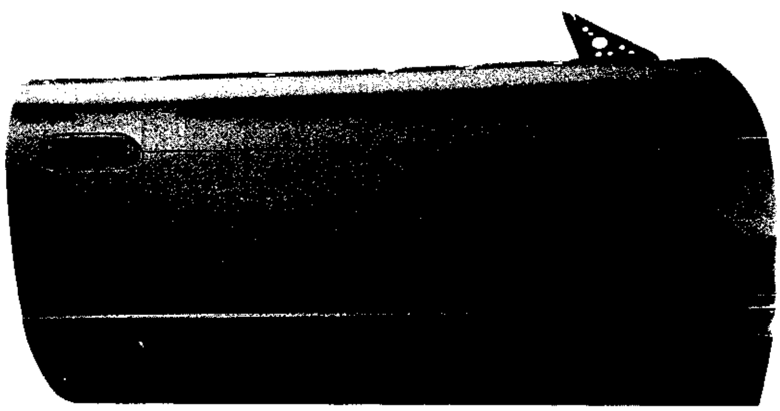

Photo 2 Door outer panel press-formed by organic composite coated sheet steel with extra-deep drawability and bake-hardenability

mer being a cold-rolled and continuous-annealed sheet steel and the latter an organic composite-coated sheet steel. Both panels require excellent press-formability and high resistance to denting. The newly developed bake-hardening high-strength sheet steels have been applied to many exposed panels in thinner gages, contributing to car weight reduction.

6 Conclusions

New cold-rolled sheet steels (including those coated) with excellent formability and high bake-hardenability suitable for thinner gage automobile exposed panels were investigated.

(1) High-temperature annealing to dissolve carbides above the recrystallization temperature and the subsequent rapid cooling of extra-low-C steels containing strong carbide-formers such as Ti and Nb provided an intense {111} recrystallization texture that is favorable for deep drawability and some amount of solute C that is effective for bake-hardenability.

(2) This processing principle was applied to develop extra-deep drawing cold-rolled sheet steels (C ~ 0.002%, Nb (at%)/C (at%) ~ 1.0) with bake-hardenability by using newly developed continuous annealing lines (KM-CAL) capable of high-temperature annealing at approximately 900°C.

(3) An organic composite-coated sheet steels with similar mechanical properties was also developed by applying a new organic film baked at low temperature to the continuously annealed sheet steels.

(4) Hot-dip galvannealed sheet steels with extra-deep drawability and bake-hardenability were also developed by employing newly installed continuous hot-dip galvanizing lines capable of high-temperature annealing and rapid cooling.

(5) The deterioration in mechanical properties due to ambient temperature aging is negligible within 3 months for a material with 40 MPa BH. Decreasing bake-painting temperature from 170°C to 140°C results in little decrease in the strength increment due to strain-age hardening.

(6) These new sheet steels are suitable for thinner gage automobile exposed panels such as fenders which require high press-formability and dent resistance.

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