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Past Development and Future Outlooks of Automotive Steel Sheets

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Abstract:

The 40-year history of automotive steel sheet development is reviewed, centering on deep drawing quality cold-rolled steel sheet, high-strength steel sheet and coated steel sheet, and the future outlooks of their development are presented. When multinationalization, international competition, safety and recycling issues and global environmental protection are taken as challenges facing the automobile industry, now is the time to study the future course of automobile development and build a new automotive steel sheet manufacturing setup. Important considerations in this innovation are to keep an adequate balance between functionality and price and to integrate conventional steel sheet products for international adaptability. To make automotive steel sheets recyclable, their chemical compositions and manufacturing conditions must be drastically reviewed as the staring point. The recycling issue calls for the automobile and steel industries to work together toward the final goal.

1. Introduction

When we look back into the 40-year history of development of automotive steel sheets in Japan, we realize that it has been a history of deepening cooperation between the automobile and steel industries. Through the past years, the steel industry has undertaken the development and stable mass production of high-performance, high-quality steel sheets as demanded by the automobile industry while reflecting the current social needs from time to time. It deserves special mention that the automakers and steelmakers have undertaken various joint studies to apply newly developed steel sheets to automobiles and made many brilliant achievements.

The future automotive steel sheet development will be directed toward assuring the crash safety of automobiles, satisfying strict fuel economy regulations, and recycling used automobiles. While retaining their importance as automotive materials, steel sheets will be called upon to acquire such new characteristics that meet future social needs. The past developments and future outlooks of automotive steel sheets are described below.

2. Changes in Major Steel Manufacturing Technologies

Fig. 1 shows the changes in automobile and steel production volumes and in major steel manufacturing technologies in Japan. During the postwar economic recovery periods, the automobile industry introduced passenger car production technologies from

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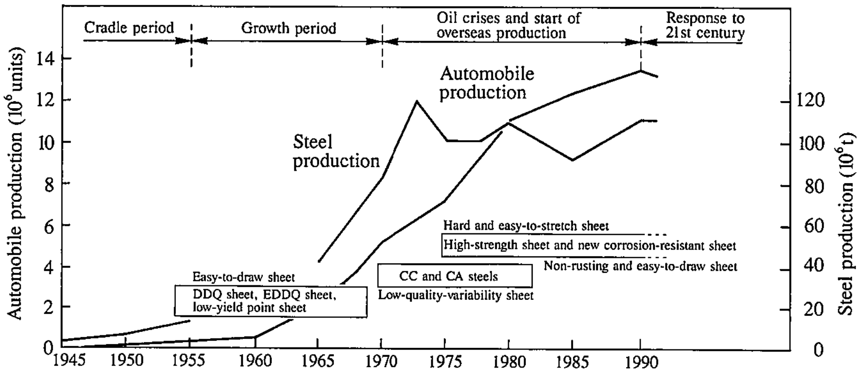

Automobile industry	Passenger car production approved Technology introduction	Equipment modernization Mass-production system established Safety and pollution control	Oil crises Automation Higher yen and overseas production Compact cars	• Global environmental protection • Resource and energy savings • Multinationalization • User preferences
Steel industry	Technology introduction	Steelworks built near consuming areas Equipment size expansion BOFs Vacuum degassers	Process integration Continuous casting and continuous annealing High-functionality products Coating lines	

Fig. 1 Changes in main steel production technologies

abroad and started domestic production. The steel industry for its part imported rolling mills and sheet manufacturing technologies from advanced countries and acquired capabilities to produce deep drawing quality sheet from low-carbon aluminum-killed steel.

In the late 1950s to the early 1960s, the automobile industry established mass production systems and pursued production rationalization through equipment modernization. The steel industry started the construction of latest steelworks, such as Nippon Steel's Nagoya and Kimitsu Works, and augmented steel production facilities to support the mass production systems of the automobile industry. During the same period, many facilities that would become the core of steel manufacturing technologies in the years to come, such as basic oxygen furnaces, vacuum degassers, open-coil annealing furnaces and continuous slab casters, were constructed and commissioned. Making the most of these state-of-the-art facilities, the steel industry developed steel sheets of higher performance and quality, such as deep drawing quality (DDQ) sheet, low-yield point sheet and extra-deep drawing quality (EDDQ) sheet one after another to meet the increasingly sophisticated needs of customers.

The 1970s was a period of oil crises and economic multinationalization. The oil crises had a serious impact on the automobile industry. To overcome the oil crises, Japan innovated automobile production technologies and in that course became the world's largest automobile producing country. In the meantime, the steel industry strived to develop new products to meet diversifying needs. Production technologies developed during this period include continuous casting for high-grade steels, shape control with six-high mills, continuous annealing, and wide-strip electroplating. These latest technologies proved instrumental in the mass production of commercial grade steel sheet, high-strength steel sheet, and corrosion-resistant steels sheet.

The period from 1985 to date has been one of stable economic growth, marked by stabilizing demand structure, intensifying international competition and tie-up, and increasing multinationalization of production. Environmental protection on a global scale has also been highlighted. Among the problems to be tackled toward the 21st century, the future outlooks of automotive steel sheets are discussed below, focusing on deep drawing quality cold-rolled steel sheet, high-strength steel sheet, and coated steel sheet.

3. Deep Drawing Quality Cold-Rolled Steel Sheet and Extra-Deep Drawing Quality Steel Sheet

Deep drawing quality (DDQ) cold-rolled steel sheet is described first. DDQ sheet of low-carbon aluminum-killed steel was domestically produced for the first time in the late 1950s and ever since has been used in large quantities for automobiles. The deep drawability of the steel is attributable to the precipitation of aluminum nitride (AlN) during box annealing. Aluminum nitride facilitates the evolution of a recrystallized texture that enhances deep drawability. The DDQ cold-rolled steel sheet is slowly cooled after soaking during box annealing and is thus rendered non-aging.

Previously, the DDQ cold-rolled steel sheet could not be manufactured by the continuous annealing process. This was made possible by adopting a new continuous annealing heat cycle consisting of soaking, rapid cooling, reheating, and overaging[1-3]. The continuous annealing heat cycle is illustrated in **Fig. 2**, and the chemical composition and mechanical properties of the DDQ cold-rolled steel sheet are given in **Table. 1**. **Fig. 3** shows the relationship of the primary cooling end temperature with the aging index (AI) and the amount of bake hardening (BH). The continuous annealing process can produce nonaging sheet (AI ≤ 30 MPa) and bake-hardening sheet by selecting the primary cooling end temperature.

The DDQ low-carbon aluminum-killed steel sheet contains about 0.02 mass% carbon and can be thus increased in as-welded strength and fatigue strength. Its bake hardening property makes it a useful material for automobile weight reduction. It does not contain titanium and other microalloying elements and is a material helpful in promoting the recycling of used automobiles. Further development of this type of material with functions to meet future needs in terms of both manufacturing technology and application technology will be one of the future directions of automotive steel sheet developments.

Extra-deep drawing quality (EDDQ) steel sheet is discussed next. Ultralow-carbon (ULC) steel sheet was made readily manufacturable by the progress of vacuum degassing technology.

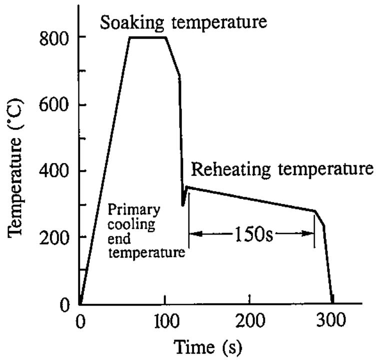

Fig. 2 Continuous annealing heat cycle for manufacture of nonaging aluminum-killed steel sheet

Table. 1 Chemical composition and mechanical properties of DDQ cold-rolled aluminum-killed steel sheet produced by continuous annealing process

Chemical compostion (mass%)						Mechanical properties				
C	Mn	P	S	Sol Al	N	$\bar{r}$ value	El (%)	YP (MPa)	TS (MPa)	AI (MPa)
0.018	0.15	0.012	0.013	0.074	0.0020	1.73	46	167	310.7	26

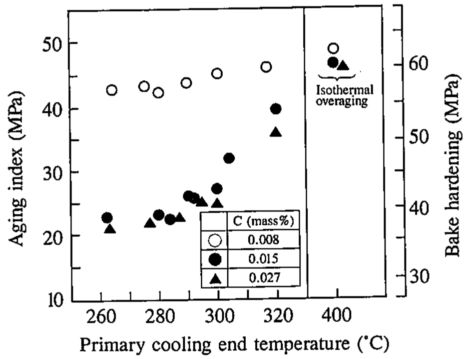

Fig. 3 Effects of carbon content and primary cooling end temperature during continuous annealing on aging index (and corresponding bake hardening) of DDQ cold-rolled aluminum-killed steel sheet

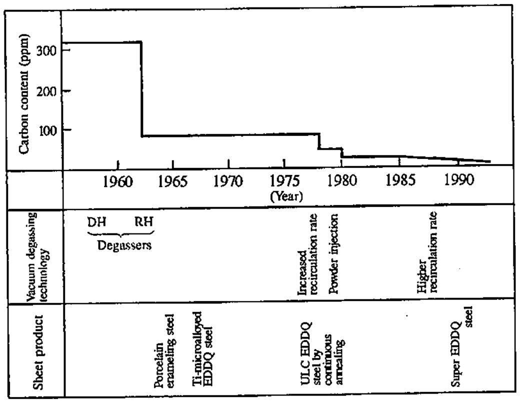

Fig. 4 Changes in steel carbon content reduction technology and steel carbon content

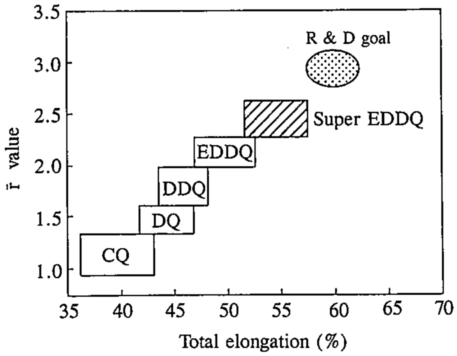

Fig. 5 Grades and mechanical properties of cold-rolled steel sheets (CQ for commercial quality, DQ for drawing quality, DDQ for deep drawing quality, EDDQ for extra-deep drawing quality, and super EDDQ for super extra-deep drawing quality)

Fig. 4 shows the change in the steel carbon content by period. The manufacture of EDDQ sheet was made possible by addition of titanium and/or niobium to the ULC steel and utilization of high-temperature annealing in the continuous annealing stage. The EDDQ sheet has an $\bar{r}$ value of about 2.0 and features extremely good deep drawability as shown in **Fig. 5**. The recent progress of vacuum degassing technology has enabled the production of ULC sheet with a carbon content of about 20 mass ppm and of super extra-deep drawing quality (super EDDQ) sheet with an extremely high $\bar{r}$ value of about 2.5[4,5].

The deep drawability of steel sheet has improved along with increasing purity of steel. Can deep drawability be improved further? Will it be possible to manufacture steel sheet with an $\bar{r}$ value of 3.0 or more and total elongation of 60% or more as indicated as the R & D goal in **Fig. 5**? The studies currently conducted to improve the deep drawability of cold-rolled steel sheet are introduced below.

The recrystallized texture orientation that provides steel sheet with the highest possible $\bar{r}$ value can be achieved by developing the {111} planes parallel with the rolling plane of the sheet. An iron sheet with fully developed {111}<110> orientations was test produced from high-purify electrolytically deposited iron[6]. **Fig. 6** shows the {100} pole figure of the iron sheet. The chemical composition and mechanical properties of the iron sheet are given in **Table. 2**. The electrolytically deposited iron sheet recorded an $\bar{r}$ value of 2.8 and total elongation of 57%. This means that the R & D target $\bar{r}$ value and elongation shown in **Fig. 5**[7] are not unrealistic values. It is predicted that steel purity improving technology will make further progress and that super-ultralow-carbon steel sheet with a carbon content of 4 mass ppm[8] will be commercially produced by the year 2000. Steel sheet with such an ultimate deep drawability will undoubtedly occupy one niche in the automotive steel sheet market in the future.

4. High-Strength Steel Sheets

The steel industry started work on the development of high-strength steel sheets for automobiles in about 1970. The high-strength steel sheets were intended for safety cars. Since the high-strength steels were designed to absorb the crash energy of automobiles, they did not need high formability as sheet products. The crash energy absorption was accommodated by titanium- or niobium-microalloyed precipitation-strengthened steel and silicon- or manganese-microalloyed solid-solution strengthened steel.

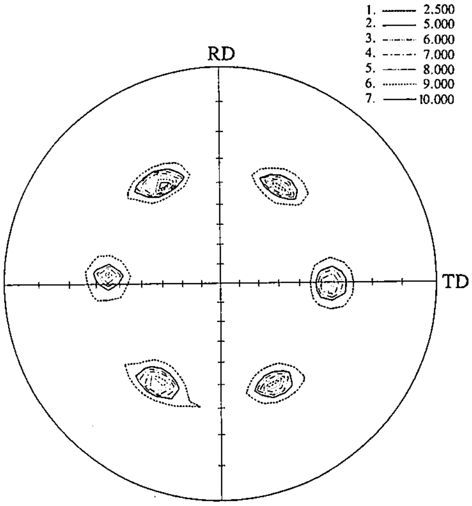

Fig. 6 {100} pole figure of recrystallized texture in high-purity electrolytically deposited iron sheet

Table. 2 Chemical composition and mechanical properties of electrolytically deposited iron sheet

Chemical composition (mass%)								Mechanical properties						
C	Mn	Si	P	S	Al	N	O	$\bar{r}$ value				El (%)	YP (MPa)	TS (MPa)
								r_L	r_C	r_D	$\bar{r}$			
8	1	1	1	6	2	2	10	2.8	2.7	2.9	2.8	57	127	245

The 1973 oil crisis prompted the use of high-strength steels for automobile weight reduction. High-strength steels with excellent formability had to be developed for hard-to-form panels and undercarriage parts. To meet this challenge, the continuous annealing technology that had just appeared was utilized, and phosphorus-bearing aluminum-killed high-strength steel with a well-balanced $\bar{r}$ value and yield ratio, bake-hardening high-strength steel, and interstitial-free (IF) steel with a high $\bar{r}$ value were developed. **Fig. 7** shows the characteristic mechanical properties of these high-strength steels for automobile body panels. These steel sheets were begun to be used in mass-production automobiles after the second oil crisis of 1978. Dual-phase steel with a tensile strength of 500 to 600 MPa was developed as sheet for structural members and undercarriage parts. This steel has a microstructure composed of ferrite and martensite, low yield point, large elongation, and high formability. Suspension parts of complicated shape are made from hot-rolled high-strength steel with flangeability enhanced by carbide and sulfide shape control.

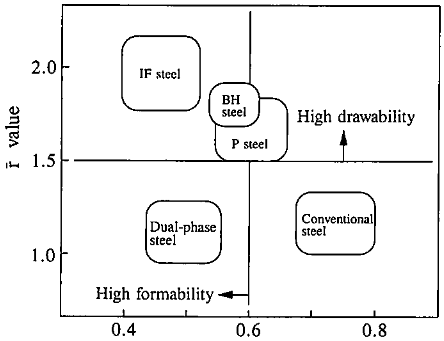

Fig. 7 Characteristic mechanical properties of high-strength steel sheets for automobile body panels

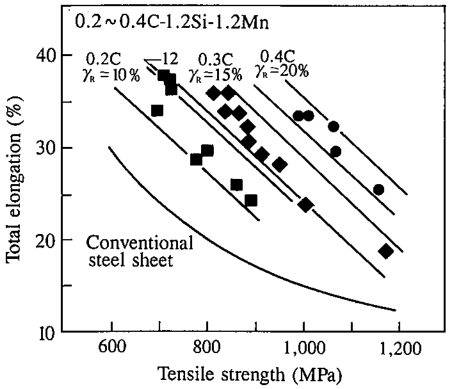

Fig. 8 Effect of amount of retained austenite on tensile strength-total elongation balance of retained austenite steel sheet

High-retained austenite steel[9] that makes use of transformation-induced plasticity and copper-bearing steel[10] that makes use of the high heat treatment strengthening capability of copper are under development as high-strength steel sheet for very lightweight automobiles[11]. Each steel features a strength of 600 MPa or more and formability of the 400 MPa class. **Fig. 8** shows the relationship between the strength and elongation of the high-retained austenite steel. A 1,200-MPa steel was developed for door impact beams and is finding increasing usage in that application.

As described above, various types of high-strength steels have been developed to suit specific automotive applications. **Fig. 9** shows the relationship between the strengthening mechanisms and the strength-total elongation balance of automotive high-strength steel sheet. Future automobiles will be made of steel sheets of higher than ever strength from the standpoint of reducing the car weight for higher fuel mileage and securing passenger safety. The high-retained austenite steel that provides both high strength and formability is expected to advance further among the high-strength steel sheets developed to date. It will find use in a gradually increasing number of automotive parts.

One important issue for the automobile industry is the recycling of used automobiles. Conventional high-strength steel sheets have used various strengthening elements. these strengthening elements must be reevaluated from a steel recyclability

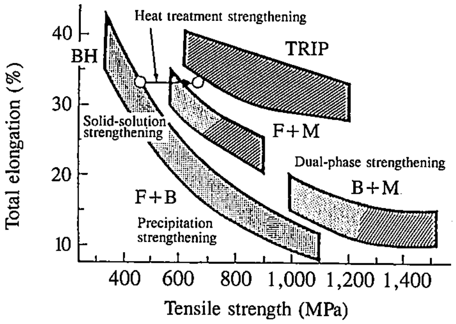

Fig. 9 Relationship between strengthening mechanisms and tensile strength-total elongation balance of automotive high-strength steel sheet (F for ferrite, B for bainite, M for martensite, BH for bake hardening, and TRIP for transformation-induced plasticity)

point of view to build a manufacturing system for high-recyclability steels. The steel industry and the automobile industry will have to work together in developing technologies for producing, working, and using such high-recyclability steel sheets.

5. Coated Steel Sheets

Among the coated steel sheets used in automobiles are corrosion-resistant steel for body panels, aluminum-coated steel for exhaust system parts, and terne-coated steel for fuel tanks. Here, the automobile body corrosion-resistant steels that involve many technologies and have drastically grown in production volume are taken as one example. The technological background of their growth and diversification as well as their future issues are discussed below.

Fig. 10 shows the changes in automobile production and automobile body corrosion-resistant steel sheet shipment in Japan. The demand for corrosion-resistant steel sheet was furthered by the necessity of protecting automobile body panels against corrosion by road deicing salt used in large quantities in frigid regions, and of reducing the automobile weight as triggered by the two oil crises. The need for higher corrosion protection and the growth of domestic automobile production steadily increased the production of corrosion-resistant steels with diversifying product types from the early 1980s. Starting in 1991, however, a serious structural recession sharply reduced the demand, forcing production to be cut down.

The changes in the type of corrosion-resistant steel sheets for autobody panels in Japan are shown in **Fig. 11**[12]. The first corrosion-resistant steel sheet for body panels in Japan was one-side ground galvannealed steel (GA). This corrosion-resistant steel was then replaced by two-side two-layer zinc-iron alloy-electroplated steel for better protection of outer panels. Next came two-layer galvannealed steel that provides a heavier coating weight for improved resistance to perforation corrosion. Zincrometal, an organic-coated sheet product developed in the United States, was successively modified for enhanced corrosion resistance, formability and weldability, to develop into an organic composite-coated steel sheet having a very thin organic film applied to a zinc-nickel alloy electroplated coating. These coated steel sheets were developed by steelmakers in close cooperation with automakers, with Nippon Steel playing a major role.

The types of corrosion-resistant steel sheet to be selected for automobile body panels widely vary according to the corrosion protection, concept of individual automobile manufacturers. This is the reason why there are two different types now available in Japan as mentioned above. Each steel is claimed to satisfy the present corrosion protection targets of 10 years of perforation corrosion resistance and 5 years of cosmetic corrosion resistance. **Fig. 12** shows the perforation corrosion resistance of various corrosion-resistant steel sheets. The perforation corrosion performance depends not on the coating type but on the coating weight, and improves with the presence of a two-layer coating or organic coating.

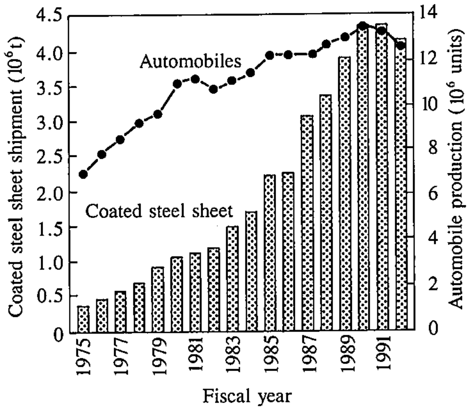

Fig. 10 Changes in automobile production and coated steel sheet shipment

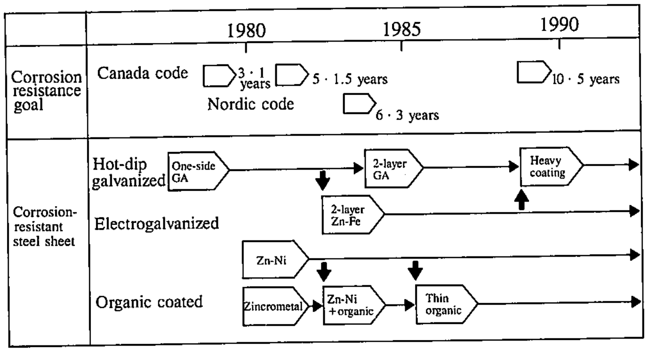

Fig. 11 Changes in corrosion-resistant steel sheets

In the development of corrosion-resistant steel sheet, it is a major consideration to improve such service properties as weldability and paintability in addition to corrosion resistance as well as surface quality and paint finish. It is equally important to take into consideration the relationship between corrosion protection technology and base steel in carrying out the development work. For instance, the type of super EDDQ steel or high-strength steel to be used may vary according to whether the corrosion-resistant coating is by the electrolytic or hot-dip process. The relationship between the base steel to be selected and the coating to be applied has been comprehensively studied with a view to fully satisfying the customer needs.

As Japanese transplants started automobile production abroad in the late 1980s, the international adaptability of the corrosion-resistant steel sheet that had developed while meeting the requirements peculiar to the Japanese automobile industry was called into question. Now that the Japanese automobile and steel industries are restructuring themselves, some doubt is cast about the diversity of available corrosion-resistant steels. We will have to tackle the development of coated steel sheets taking these ques-

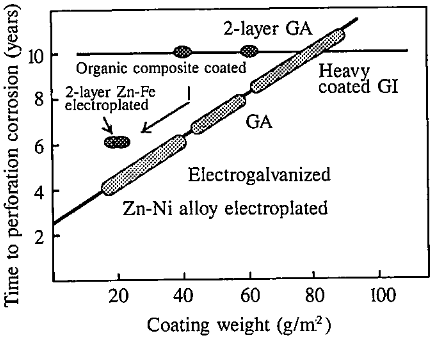

Fig. 12 Perforation corrosion resistance and course of development of corrosion-resistant steel sheets

tions into account.

6. Conclusions

The 40-year history of deep drawing quality steel, high-strength steel, coated steel and automotive steel developments has been reviewed, and the future directions of automotive steel sheet development have been presented. If the future surroundings of the automobile industry are signified by multinationalization, international competition, safety, recyclability, and global environmental protection, now is the time to review the course of development of automotive steel sheets and to build new automotive steel sheet manufacturing systems. Construction of such a new automotive steel sheet manufacturing system makes it necessary to consolidate the present automotive sheet grades into internationally adaptable ones while maintaining an optimum balance between functionality and price. If automotive steel sheets are to be rendered recyclable, their chemical compositions and manufacturing conditions must be fundamentally reviewed as the starting point. The automobile and steel industries must join forces to this end.

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