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Nb Application to Automotive Steel Sheets

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Abstract

The automobile and steel industries are closely linked by a strong customer - supplier relationship. The application of high strength sheet originated from social needs. The keen issue for automakers in recent years has been to reduce the weight of the automobile body while maintaining sufficient safety by using high strength steel sheet to ensure both fuel efficiency and crash worthiness. The characteristics of the steel sheets for an automotive body have changed drastically according to changes in demand. In this paper, the exact metallurgical background and mechanical properties of hot rolled steel sheets used for chassis and cold steel sheets used for body are introduced.

Introduction

The automobile and steel industries are closely linked by a strong customer - supplier relationship. The application of high strength sheet originated from social needs. Due to an increase in vehicle accidents with the motorization of the 1960s, the US government established the Federal Motor Vehicle Safety Standard (FMVSS) in 1968. The automotive industry began to adopt high strength steels for use in car parts like bumpers, door reinforcements and brackets. Before the FMVSS, technology activities in automotive steel sheets were mainly focused on the improvement of formability in mild steel. Following the oil crises in the 1970s, high strength steels that reduced the thickness of steel sheets in inner panels and outer panels were developed. In the 1970s, the first continuous annealing facility was commercialized in Japan. This technological innovation formed a turning point in the improvement of productivity and quality of automotive steel sheets, which now demonstrated a wide range of strengths and deep drawing qualities. The key issue for automakers in recent years has been to reduce the weight of the automobile body while maintaining sufficient safety by using high strength steel sheet to ensure both fuel efficiency and crash worthiness. The characteristics of the steel sheets for an automotive body have changed drastically according to changes in demand.

As shown in Figure 1, hot rolled steel sheets are applied to chassis parts such as suspension arms, cross members and wheels. The majority of these applications are made with 540-590 MPa steel grades. The 780 MPa grade was applied to wheels about 10 years ago and successfully applied to the lower arm application. The application of the 780 MPa grade is still limited.

Cold rolled sheets are applied to the body-in-white. A typical example of the steel sheets used in the bodies of recent Japanese small cars shows the ratio of high strength steel sheet is more than approximately 50% in this vehicle (Figure 2). The 590 MPa grade is applied to the side rail, Bpillar, roof rail and rocker to ensure crash worthiness [1]. Interstitial Free (IF) steel is one of the important materials in automobiles and covers from extra mild steel to 440 MPa tensile strength.

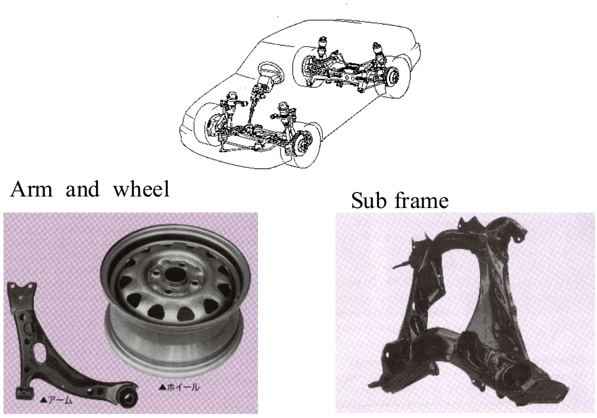


Figure 1. Example of recent application of hot rolled high strength steel sheets.

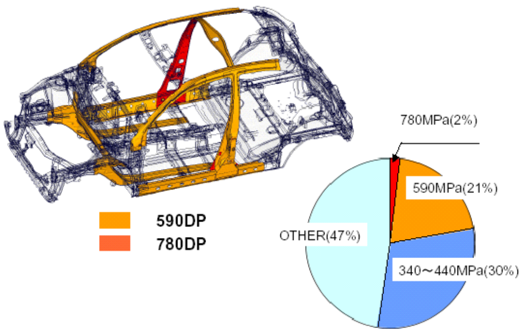


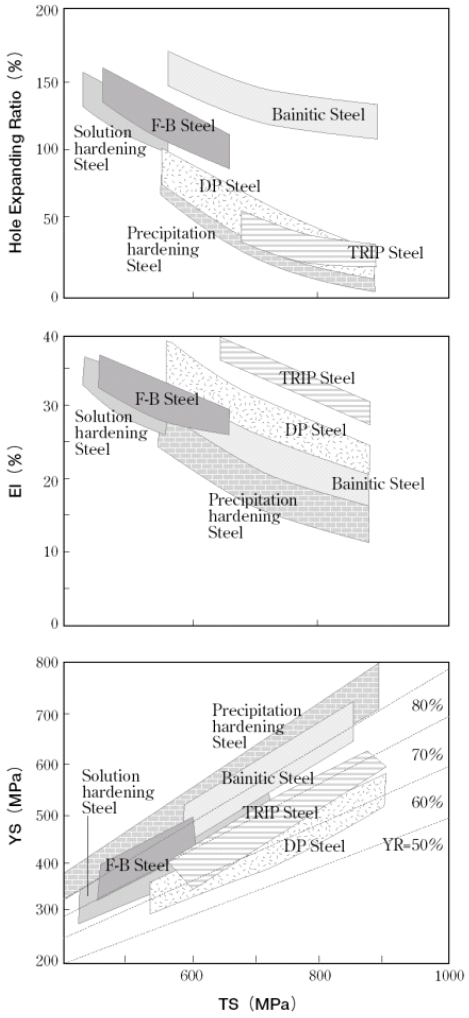
Figure 2. Example of recent application of high strength steel sheets in a small size vehicle in Japan.

Hot Rolled Steel Sheet

Hot rolled steel sheets are applied to the chassis and wheels. When hot rolled sheets are applied to these parts, not only high El (Total Elongation), but also high stretch flangeability, as evaluated by the hole expansion ratio, is strongly demanded. The relationship between TS (Tensile Strength) and hole expansion ratio, El and YS (Yield Strength) of various kinds of hot rolled steel sheet is important to understand the characteristics of steels used in automobile, as shown in Figure 3. Bainitic steel shows the highest TS-hole expansion balance over a wide range of TS. However, El is relatively low and YR (Yield Ratio, YS/TS) is high. F-B (Ferrite-Bainite) steel shows high hole expansion ratio and high El. Although TRIP and DP steels show high El, hole expansion ratio remains at low values. Solution hardening steel cannot give higher TS than 590 MPa. Precipitation hardened steel (HSLA, High Strength Low Alloy Steel) showing the microstructure of ferrite and pearlite was the primary high strength steel sheet employed as high strength steel sheet started to come into use, but its application is now limited due to its limited El and stretch flangeability. IF steel, which is one of the main steel grades in cold rolled sheet, is not commonly applied to these parts.

Ferrite-Bainite steel

Ferrite-Bainite steel is widely applied to chassis and wheels, because it has excellent stretch flangeability and relatively high El. The relationship between TS and stretch flangeability evaluated by hole expansion ratio in various kinds of microstructural steel are shown in Figure 4. F-B, F-P and F-M stand for Ferrite-Bainite, Ferrite-Pearlite and Ferrite-Martensite steel respectively. This microstructure is obtained by changing the coiling temperature from RT (Room Temperature) to 650°C using 0.05C-0.5Si-1.6Mn-0.025Nb (%) steel (Steel A) and 0.07C-0.5Si-1.6Mn-0.5Cr-0.038Nb (%) steel (Steel B). F-B steel coiled at 450°C shows excellent stretch flangeability compared with F-M steel (DP steel) coiled at RT and F-P steel (conventional HSLA steel) coiled at 650°C [2, 3]. The effect of hardness of second phase on the reduction of area, ε_f, and strain to void initiation, ε_i, measured by round specimens taken from hot rolled steel A are shown in Figure 5. It proves that the reduction of area, ε_f, shows good agreement with hole expansion ratio in the same literature reference. Figure 5 indicates that the hardness of second phase corresponds well to ε_f and ε_i. The hardness of ferrite matrix had the same value for all specimens. This means that the smaller hardness ratio between the ferrite matrix and the second phase results in the inhibition of void formation at the boundary of ferrite and second phase and also, a high hole expansion ratio. In addition, the predominance of ductility in bainite itself contributes to high ε_i.



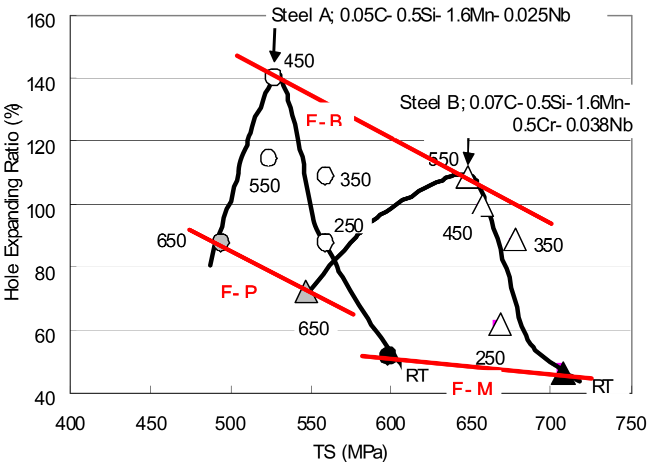


Figure 4. Relationship between TS and hole expansion ratio in various kinds of microstructural steel.

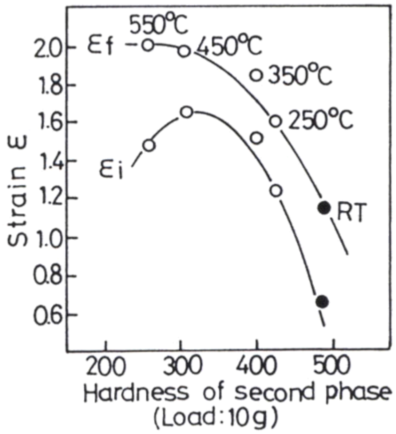


Figure 3. Relationship between TS and YS, El and hole expansion ratio in various kinds of hot rolled steel sheet.

Figure 5. Effect of hardness of second phase on the reduction of area, ε_f , and strain to void initiation, ε_i , measured by round specimens taken from hot rolled steel A.

Bainitic steel

As can be assumed from the discussion before, the ideal microstructure for high hole expansion ratio is single phase. With this in mind, a 780 MPa bainitic ferrite steel grade was developed. Since no second phase was included in this steel, a high hole expansion ratio could be attained. The elimination of cementite, which is one of the origins of micro cracks, also contributed to the improvement of the hole expansion ratio [4].

DP steel and TRIP-aided steel

Bleck et al. [5] precisely explained the concept of alloying elements for the control of microstructure in DP steel and TRIP steel. Nb in a state of solid solution retards static and dynamic recrystallization during hot rolling as well as austenite to ferrite transformation. Small carbonitrides also delay recrystallization and result in significant strengthening. The addition of Nb to DP steel provides noticeable grain refinement and thus improves higher strength ductility. DP steel is applied to wheel disks because of high El and fatigue properties.

Many researchers in the world are interested in the production of hot rolled TRIP steel. Hashimoto et al. [6] showed that the addition of Nb is effective in improving strength and elongation balance.

As shown in Figure 6, the highest TSxEl with TS of 780 MPa was obtained when the steels were coiled at 400°C. This condition corresponded to the condition showing the highest volume fraction and carbon concentration of retained austenite. Hashimoto and his team explained that the reason for good ductility in 0.05% Nb containing steel was mainly due to the large volume fraction and high carbon concentration of retained austenite. In addition, finely dispersed retained austenite also contributed to the improvement of ductility. Cho et al. [7] also reported that POSCO had developed 780 MPa TS grade hot-rolled TRIP steel with a Nb addition. They investigated the process by optimizing the alloying elements and mill conditions in the laboratory and hot strip mill, and successfully produced and applied the process to front sub-frames.

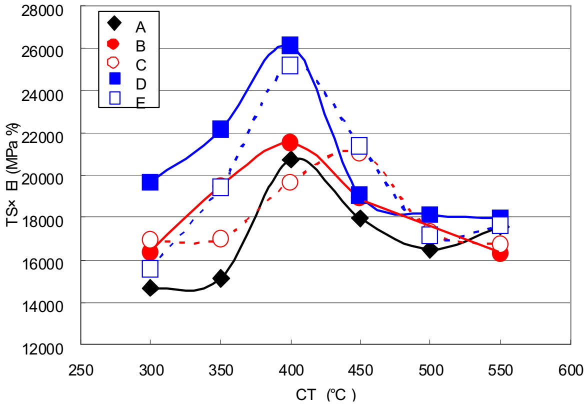


Figure 6. Effect of CT and alloying elements on TS and El balance expressed by TSxEl.

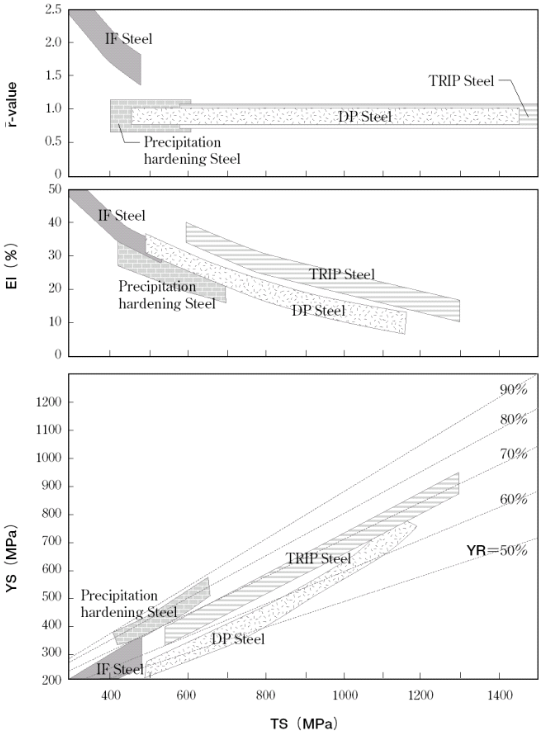


Figure 7. Relationship between TS and YS, El and r-value in various kinds of cold rolled steel sheet.

Cold rolled steel sheet

For unexposed panels such as inner door panels and side panels, steel sheets with excellent drawability, as evaluated by r-value (Lankford value), and stretch formability, as evaluated by elongation, are absolutely required. For exposed panels such as doors and hoods, steel sheets with high yield strength are required in order to help insure dent resistance as well as good press formability. However, using current press technology, yield strength must not exceed 240 MPa in order to prevent surface deflection in panel products. For this reason, BH (Bake Hardenable) steel is applied. The steel sheets used in these parts are mainly IF steels. The strength level of these steels is up to 440 MPa grade.

The relationship between TS and r-value, El and YS in various kinds of cold rolled steel sheet is summarized in Figure 7. The only steel that can give a high r-value is IF steel. The r-value of other steels is around 1.0. IF steel also has good El and low YR, however, its TS are limited to low levels. The maximum TS in commercial products is 440 MPa. TRIP steel shows excellent El in a wide TS range. After TRIP steel, DP steel shows the highest El with low YR. Precipitation hardening steel shows the lowest El and highest YR. Bainitic steel and martensitic steel have been developed as ultra high strength steel sheets in Europe and are widely applied. DP steels higher than 980 MPa are commercially produced and applied in structural parts and reinforcement door impact beams.

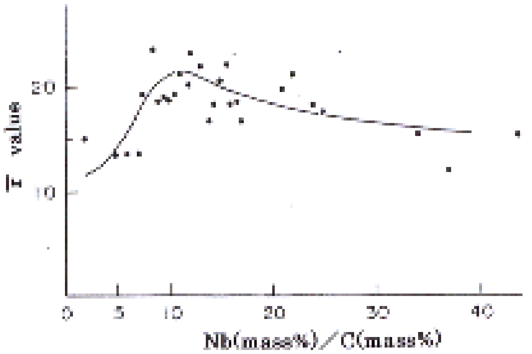


Figure 8. Effects of Nb on r-values of box-annealed sheets. Annealing condition; 780 ℃ x 5hr

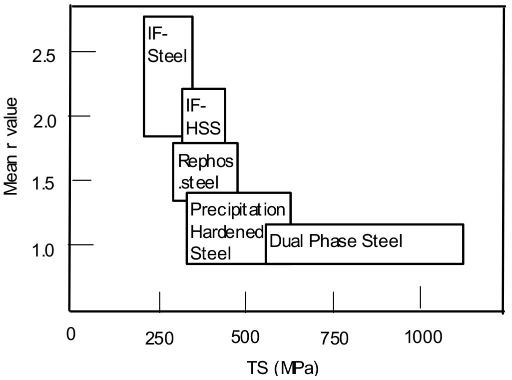


Figure 10. Relationship between TS and r-value in various kinds of steels.

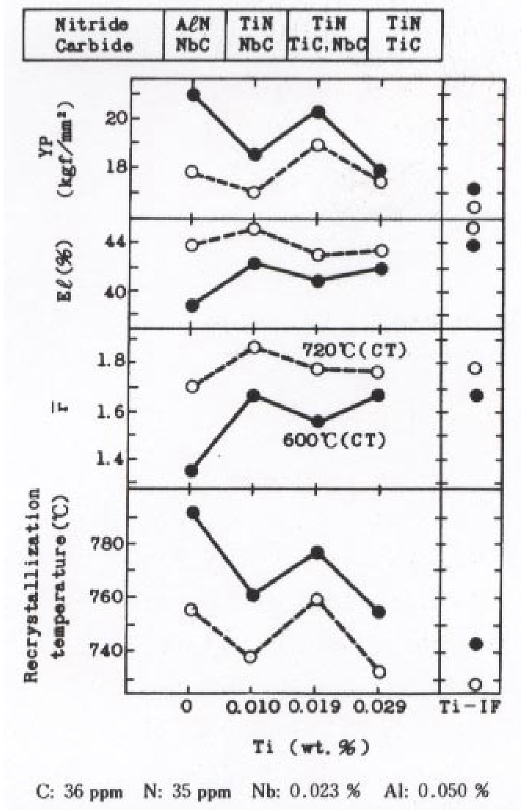


Figure 9. Effect of Ti content on the mechanical properties of 0.023% Nb-Ti-IF steels.

IF steel

Deep drawability, as evaluated by the r-value, is one of the most important characteristics for application to automotive panels. Since the invention of IF steel at the end of the 1960s, the mechanisms for attaining high r-value have been discussed. The metallurgical factors for the improvement of r-value are pointed out as follows:

1) Scavenging effect by fixing carbon and nitrogen as stable precipitates
2) Grain growth during annealing
3) Grain refinement of hot band
4) Cold reduction
5) Texture of hot band

The scavenging effect is the most important mechanism leading to the high r-value of IF steel. The effect of Nb content on the mean r-value of Nb-IF steels without Al was studied. In this experiment, annealing was simulated by batch annealing. The r-value increases from 1.2, to the maximum r value, 2.0, with an increase in [Nb](mass%)/[C](mass%) to 10, which corresponds to [Nb](atomic%)/[C](atomic%)=1.3 [8]. Because the steel does not contain Al, formation of Nb(CN) as well as NbC is thought to occur, and some amount of Nb is consumed in forming Nb(CN). Thus the optimum Nb content is larger than theoretical ratio of [Nb](atomic%)/[C](atomic%) = 1, as shown in Figure 8.

When IF production first began, Nb or Ti was singly added to fix solute interstitial free atoms, C and N. It was well known that the benefit of Nb-IF was to improve r_{45} and Δr compared to Ti-IF steels. Contrary to expectations, Ti-IF steel showed the benefit of a lower recrystallization temperature. On the other hand, these steels had certain disadvantages, such as the high recrystallization temperature of Nb-IF steel and the high Δr and bad surface property of Ti-IF steel. As a result of efforts to develop better mechanical properties, and to overcome the defects of single addition, Nb and Ti added IF steel was developed [9].

The effect of Ti addition on the mechanical properties, recrystallization temperature and nature of carbide and nitride in 0.023%Nb-IF steel is discussed and shown in Figure 9. Ti-IF steel is shown as a comparison in this figure. With the addition of Ti equivalent to the nitrogen content to Nb-IF steel, mechanical properties were very much improved compared to Nb-IF steel, especially when steels were coiled at 600°C and at the coil end when coiled at high temperatures. This is attributed to the formation of large cubic TiN precipitates instead of fine AlN precipitates formed in Nb-IF steel. If the content of Ti exceeds the amount equivalent to form TiN, the excess Ti forms fine TiC precipitates, and the yield stress tends to increase, though the mean r-value does not decrease so much in comparison to the above-mentioned case. If more Ti is added than the equivalent nitrogen and carbon content, the behavior of mechanical properties tends to become nearly the same as that of Ti-IF steel. One of the problems with Nb-IF steel was its high recrystallization temperature. By the co-addition of 0.01Ti, this temperature could be decreased 20-30 °C.

High strength IF steel

The main concern shifted from the development of IF steel with ultra-high r-value to the development of high strength IF steel as the demand for high strength steel sheets increased. The relationship between TS and r-value in various kinds of steel is summarized in Figure 10. The mild IF steel shows an r-value higher than 2.0. The best-known way to increase the TS of IF steel is to add solid solute elements such as P, Si and Mn [10]. The maximum TS attained by the addition of these elements is 440 MPa. The r-value decreases with the addition of these elements, but stays around 2.0 as shown in Figure 10. Rephosphorized steel is Al-killed steel strengthened by P addition. However, the application of this steel has decreased due to the limitation of r-value compared with IF steel. Precipitation hardening steel and DP steel cannot exhibit high r-values.

Recently, a new idea for high strength IF steel was proposed from a Japanese steel company [11]. The concept of this steel is to use grain refinement and precipitation hardening with a combination of solid solution hardening. A schematic diagram showing the metallurgical concept of the developed steel in comparison to conventional IF steel is shown in Figure 11.

The example of chemical compositions of the developed steel and conventional IF steel is shown in Table I. C and Nb contents are much higher in developed steel B than those in steel A for the purpose of grain refinement and precipitation hardening.

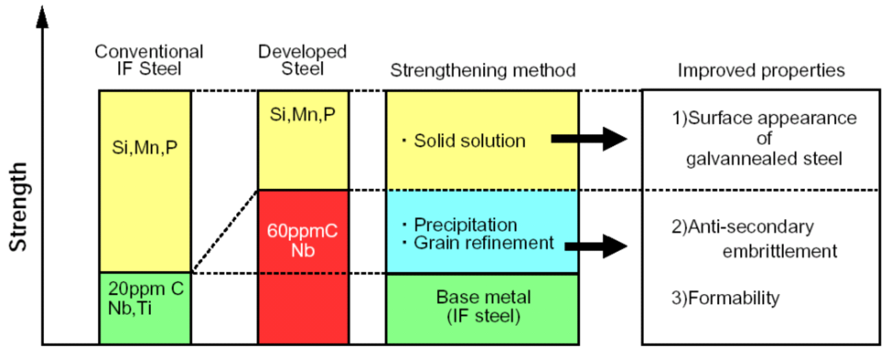


Figure 11. Schematic diagram showing the metallurgical concept of developed steel with comparison to conventional IF steel.

Table I. Chemical composition of steels (mass%).

Steel	C	Si	Mn	P	N	Nb	(Nb/ C)at
A	0.0020	0.02	0.66	0.043	0.0029	0.022	1.42
B	0.0052	0.01	0.62	0.0400	0.0032	0.068	1.69

Galvannealed IF steel

As shown in Figure 12 [12], the production of cold rolled IF sheet steels has progressively decreased year after year. In contrast, Zn coated IF steel sheets have obviously increased recently in Japan. In 1998, the production of Zn coated IF sheet steels was ahead of that of cold rolled sheets for the first time. For cold rolled sheet steels, Ti bearing IF steels can be used, however, for hot dip galvannealed IF steels, Ti-only-IF steels can not be used due to their problem in powdering. The powdering characteristics between Nb-Ti-IF and Ti-IF steels, as evaluated by the 45-degree V notch-bending test, are compared in Figure 13 [13]. At the same coating weight, Nb-Ti-IF steel exhibits a much lower powdering tendency than the Ti only IF steel. As the coating weight demanded from the automobile industry is higher than 45g/m^2, Ti-only IF steel would not be acceptable because of its poor powdering resistance.

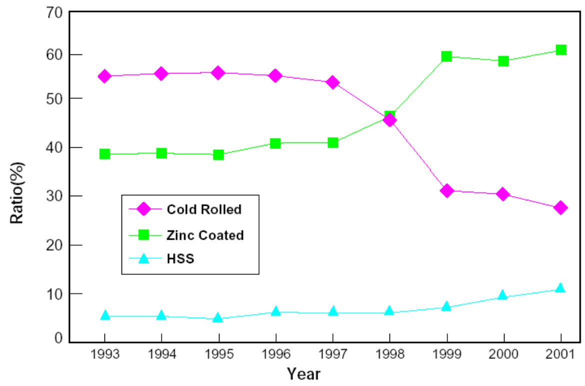


Figure 12. Periodic change in the production ratio (%) of IF steels in Japan.

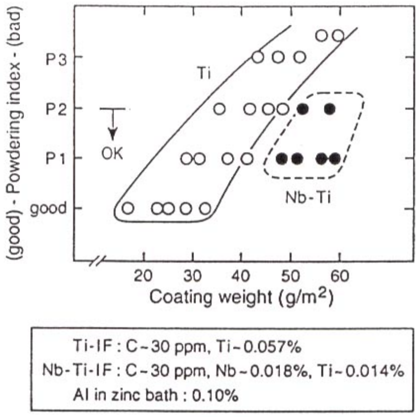


Figure 13. Powdering tendency of GA-IF steels.

The mechanism of the effects of Nb on improving the galvannealing behavior of IF steel has been discussed. Hisamatsu [14] and Nishimoto et al. [15] pointed out that the inferiority in the galvannealed surface of Ti-IF steel is caused by "out-burst" behavior. During galvannealing, Zn diffuses into the Fe_2Al_5 layer, which then diffuses into the purified grain boundaries that exist in Ti-IF steels forming the Fe-Zn intermetallic compound (IMC) at the boundaries. Volume expansion of the Fe-Zn IMC opens up the ferrite grain boundary, promoting cracking in the Fe-Al IMC. Molten Zn exudes through these cracks causing a rapid Fe-Zn alloying reaction and Fe-Zn IMC out-bursts. In the case of Nb-Ti-IF steels, solute carbon dissolved during annealing restricting the grain boundary diffusion of Zn, thereby limiting out-bursts and improving powder resistance. DeArdo [16] and Bhattacharya [17] proposed another mechanism for obtaining good powdering properties in Nb-IF steel. They proved the segregation of Nb along the grain boundary and free surface by APFIM (Atomic Power Field Ion Microscopy) and GDOES (Glow Discharge Optical Emission Spectroscopy), respectively. The segregated Nb is responsible for improved stability of the galvannealed coating.

IF steel with BH

In steels containing solute C and N, temper rolling is necessary to eliminate yield point elongation. However, the return of yield point elongation accompanied by an increase in yield strength occurs due to natural strain aging when the product is left for an extended period at room temperature. Strain aging, which causes a return of yield point elongation before press forming, has a detrimental effect on the product quality, causing a defect called stretcher-strain, being associated with yield point elongation, on the surface of press-formed parts. Therefore, a non-aging property is generally required in steel sheets to prevent stretcher-strain.

Strain aging also occurs during the paint baking of press-formed automobile parts. In this case, however, strain aging is a desirable property as it contributes to increased strength. This is referred to as bake hardening. BH steel displays excellent formability during press forming combined with high strength after paint baking. The degrees of strain aging and bake hardening are both estimated by a similar procedure based on three components: pre-strain, aging, and strain. Both yield point elongation after natural strain aging and BH after paint baking increase as the solute C content in the steel increases. Therefore, the optimum content of solute C must be determined so as to achieve a proper balance between the non-aging property and BH.

Original IF steels have an excellent non-aging property and display no BH property because the solute C and N have been completely eliminated by the scavenging effect of Nb and/or Ti. Modified IF steels with a small amount of solute C have been developed by the following processes to secure bake hardenability.

1) Control of Nb, Ti, and C contents.
   To obtain approximately 5 ppm solute C for bake hardenability, the Nb and Ti contents are reduced or the C content is increased in comparison with optimum conditions for scavenging. However, this causes some deterioration in formability.

2) High temperature annealing.
   Unlike TiC, the resultant NbC after scavenging is unstable and dissolves during high temperature annealing. Figure 14 indicates that AI increases when the soaking temperature during annealing increases [18]. Here, high AI indicates the presence of a high solute C content after NbC dissolution and corresponds to high BH. In this case, the scavenging effect before cold rolling is not reduced because NbC dissolves during annealing. Moreover, formability is improved by grain growth due to NbC dissolution during high temperature annealing. The mechanical properties of steel R2 in Figure 15 were YS of 194MPa, TS of

367MPa, El of 43%, mean r-value of 2.3, AI of 33MPa and BH of 46 MPa. Annealing temperature and holding time were 900°C for 80 s and the cooling rate was 40°C/s.

3) Addition of Cr and Mo.
According to a simulation of low C steel open coil batch annealing, the addition of 0.06 % Cr results in a BH of 40 MPa without a return of yield point elongation after strain aging at 50 ºC for 3 days [19]. In this case, Cr, which interacts moderately with solute C, considerably delays strain aging at room temperature, but BH is not markedly reduced. This effect of Cr addition is also expected in IF steels.

The effect of Mo, which interacts moderately with solute C, in a manner similar to Cr, has been confirmed directly in 0.01%Nb-0.013%Ti-IF steels. Figure 15 [20] shows that the addition of 0.025 % of Mo is sufficient to reduce yield point elongation after artificial strain aging while maintaining high BH. This effect in the reduction of aging deterioration is thought to be caused by short-range atomic interaction. The exact chemical compositions used in this experiment are shown in Table II [20].

Table II. Chemical composition of steels.

No	C	Si	Mn	P	S	Al	N	Ti	Nb	Mo	ExC
C1	20	0.04	0.5	0.03	0.008	0.035	25	0.013	0.01	0	7
C2	30										17
M1	18									0.025	9
M2	31										18
M3	25										13

C,N,Ex.C; mass ppm, the others ; mass %
Ex.C=[C]-(12/92)[Nb], where [C] and [Nb] are C and Nb contents in mass ppm

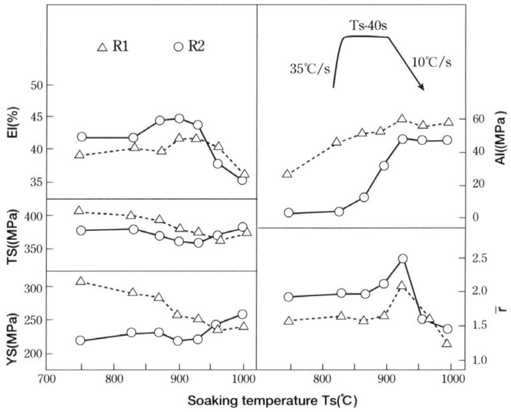


Figure 14. Variation in mechanical properties with annealing temperature.
R1: 0.004C-0.07P-0.016Nb, Nb/Cat=0.5
R2: 0.005C-0.07P-0.029Nb, Nb/Cat=0.7

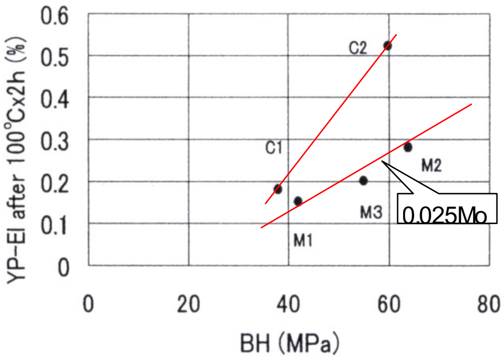


Figure 15. Effect of Mo on yield point elongation (YPEl) after artificial strain aging and bake hardening (BH) in Nb-Ti-IF steels.

DP steel

Typical DP (Dual Phase) steels contain approximately 10 vol.% of martensite in the ferrite matrix. This microstructure, like that of composite materials, results in high tensile strength and excellent ductility. DP steel sheets, mainly 590 MPa TS grade, have been applied to structural parts because of their good formability, large bake hardenability and high crash worthiness. Although the concept of DP steel was established as early as the mid-1970s, further discussion on Zn-coated DP steel, which has been its main application in recent years, has not been widely applied for manufacturing Zn-coated DP steel. A chemical composition that secures adequate Zn coatability and appropriate heat cycles, including galvannealing, must be developed.

The effect of Nb on the mechanical properties of laboratory GA steels annealed at 850°C and 900°C is shown in Figure 16 [21]. The steel used in the experiment is 0.05C-2Mn-0.5Cr-(0.05Nb) steel (mass%). Increased TS and YS of 30 MPa were obtained by the addition of 0.05%Nb. The YR was around 50% in all steels, which is sufficiently low. El and U-El were approximately 30% and 17%, respectively. The effects of the annealing temperature on strength and elongation were small. These results mean that the TS-El balance is improved by adding Nb. YPEl, which is also an important DP characteristic, was 0% in all steels. The n-value was improved from 0.20 to 0.21, and stretch flangeability was improved approximately 10 points by adding Nb.

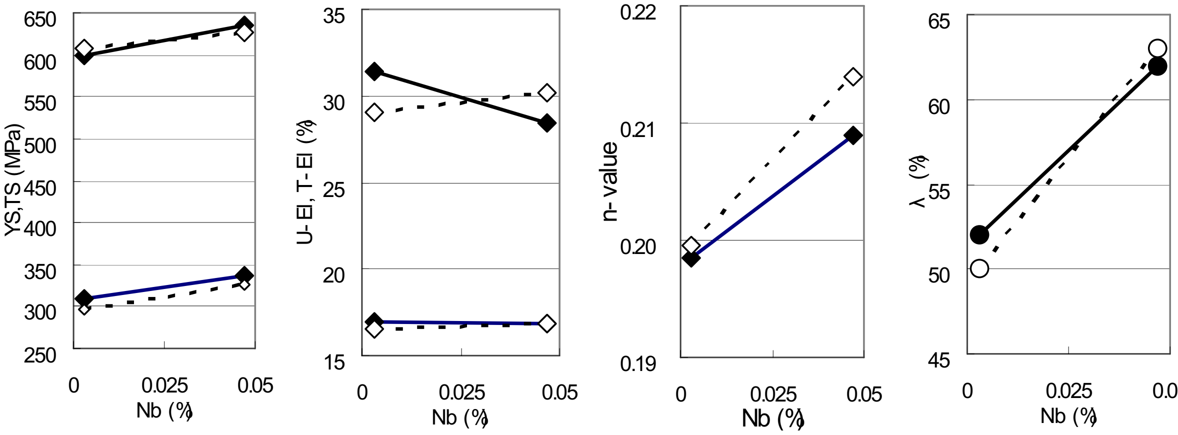


Figure 16. Effect of 0.05%Nb addition on strength, elongation n-value and stretch flangeability of GA steels annealed at 850 °C (solid mark) and 900 °C (open mark). YPEl is 0% in all steels.

Garcia et al. [22] showed that Nb added to low C steel can exhibit the same TS-El balance as conventional DP steel regardless of low annealing temperature such as 740°C for BDP-580 and 800°C for BDP-790. Chemical compositions of steels are shown in Table III. Carbon and Mn are relatively low in this grade. The 580 and 790 MPa grades contain 0.02Nb and 0.04Nb, respectively. The heat cycle was the simulation of GI process. The obtained mechanical properties are listed in Table IV.

Table III. Chemical composition and rolling conditions of experimental steels.

	Element (wt%)								Rolling Conditions		
Steel	C	Mn	Si	P	Al	Cr+Mo	Nb	N	T_{Finish}	T_{coil}	%CR
BDP-580	0.06	1.50	0.40	0.010	0.06	0.48	0.02	0.006	900°C	550°C	60
BDP-790	0.06	1.48	0.40	0.010	0.05	0.48	0.04	0.006	900°C	550°C	60

These properties are just matching those of DP steels in the TS-El diagram. Thus, this paper demonstrates that good mechanical properties can be achieved at low annealing temperatures by using low C steel with Nb additions.

Table IV. Quantitative analysis of the microstructure and mechanical properties resulting from the CGL simulation treatment.

Material	Cooling Rate (°C /s)	Grain Size of α (μm)	Vol. % of γ (measured)	YS (MPa)	UTS (MPa)	El. (%)
BDP-580	3	2.4 ± 1.0	17 ± 2.7	410	719	28
	8	2.4 ± 1.1	18 ± 3.7	408	725	25
	15	2.4 ± 1.0	21 ± 2.3	407	730	25
BDP-790	8	2.1 ± 0.8	24 ± 4.0	466	810	25
	15	2.0 ± 0.8	30 ± 3.1	489	830	24

High BH without aging is an important characteristic in DP steel. BH and AI properties were investigated using the same steels and annealing conditions as in Figure 16. The results are shown in Figure 17 [22]. 50 MPa of BH was obtained in both Nb free GA and GI steels. The BH values are nearly same as the values previously reported for DP steel. Moreover, the 0.05%Nb addition results in 5 MPa higher BH in both the GA and GI processes. The steels annealed at 900 °C showed higher BH than those annealed at 850 °C. Even with a high BH property, if the aging property of the BH steel is not appropriate, the material cannot be applied to actual automotive parts. Figure 19 also shows the AI in those steels. The 0.05%Nb added DP steels showed an AI lower than 10 MPa regardless of higher BH. This AI value means non-aging. The mechanical properties of GA steel after BH treatment (2% strain and baking at 170 °C for 20 min), or AI treatment (8% strain and aging at 100 °C for 60 min) in all 0.05%Nb added steels showed no YPEl, higher TS, and higher El than Nb-free steel after these treatments. This author explained that higher BH and lower AI are caused by the grain refinement, which occurs as a result of the addition of Nb.

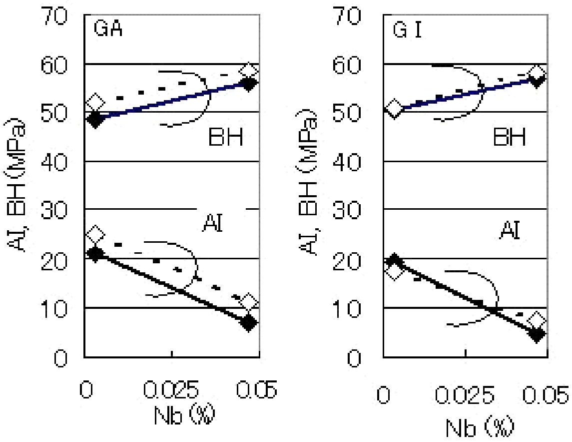


Figure 17. Effect of 0.05%Nb addition on BH and AI of GA and GI steels annealed at 850 °C (Solid mark) and 900 °C (Open mark).

Table IV. Chemical composition (mass%) of TRIP-aided steels.

C	Si	Mn	Al	Nb	Other
0.2	1.5	1.5			
0.2	0.1	1.5	1.8		
0.3	0.3	1.5	1.2		
0.15	0.6	1.5			P:0.1
0.15	0.1	1.5	1.0		Cu,Ni
0.2	1.5	1.5		0.04	
0.2	1.1	1.5		0.04	Mo:0.3

TRIP-aided steel

In producing TRIP-aided steels with a large content of retained austenite in a bainite matrix, austempering treatment is employed in continuous annealing lines with an over-aging zone. The retained austenite in TRIP steels transforms to martensite during cold forming, resulting in a combination of high tensile strength and excellent ductility. The typical alloy contents of TRIP steels are listed in Table V [23]. The alloy design in this case is based on the following principles.

1) As in DP steels, the stabilization of austenite is necessary. Thus, higher C and Mn contents are required because austenite with enriched C and Mn contents is stable even at low temperatures. Mo, Ni, and Cu also contribute to austenite stabilization.
2) Generally, supersaturated C in bainitic ferrite precipitates as fine carbide particles, resulting in the formation of a bainitic structure. However, when carbide precipitation is retarded, supersaturated C diffuses to austenite during holding at an intermediate temperature after primary cooling, thus retarding bainite formation and promoting C enrichment in the austenite. A Si addition is effective in obtaining this effect because Si retards carbide precipitation in bainitic ferrite.
3) The effects of Al and Nb in retarding bainite formation are similar to that of Si. The effect of Nb in TRIP steels has been investigated in detail [23]. For example, as shown in Figure 18, a high volume fraction of retained austenite in Nb-bearing TRIP steel is obtained at wider austempering temperatures and times in comparison with Nb-free steel.

High or ultra high strength TRIP-aided steel was developed by Sugimoto et al. [24] and results are shown in Figure 19. The matrix is bainitic, but polygonal, ferrite as in the above mentioned TRIP steel. At a TS less than 880 MPa, complex additions of 0.05%Nb and 0.2%Mo enhanced El and raised the optimum austempering temperature to 450-500°C, which corresponds to the hot dip galvanizing temperature. The TS of steels austempered from 400°C to 500°C were 800 to 900 MPa. Nb added steel showed about 50 MPa higher TS than Nb free steel. In a TS range of more than 980 MPa, complex additions of 0.02%Nb and 0.1%Mo enhanced stretch flangeability and hydrogen embrittlement performance. The former was primarily caused by a uniform fine bainitic ferrite lath structure and retained austenite films, while the latter was associated with retained austenite films trapping most of the solute hydrogen, as well as the fine microstructure.

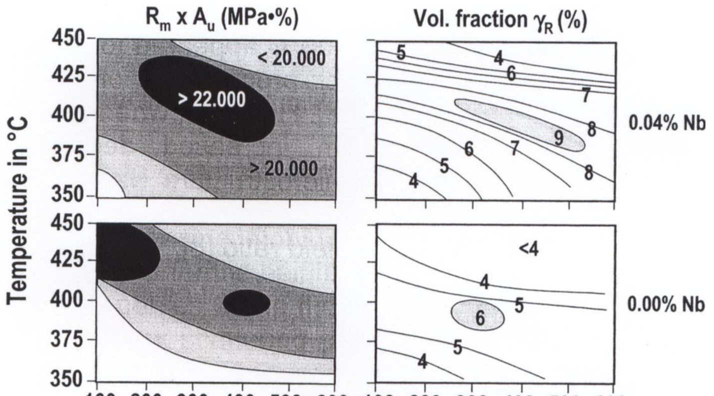


Figure 18. Effect of Nb on the volume fraction of retained austenite and TS-El balance in TRIP-aided steels for different process parameters in 0.17C-1.5Si-1.4Mn (mass%) steel.

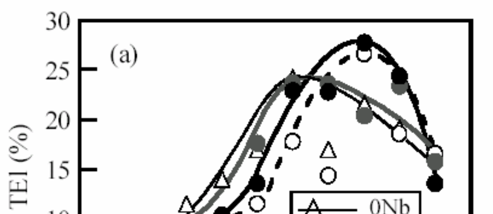


Figure 19. Effects of Nb content and austempering temperature (TA) on total elongation (TEl).
0Nb: 0.2C-1.5Si-1.5Mn steel

2Nb: ditto +0.02Nb-0.1Mo steel
5Nb: ditto +0.048Nb-0.2Mo steel
8Nb: ditto +0.077Nb-0.2Mo steel

Conclusion

The sheet steels applied to automobiles were reviewed and the following conclusions were made:

1) Hot rolled steel sheets are applied to the chassis and wheels. Stretch flangeability is an important characteristic as well as El for these applications. Ferrite-bainite steels are widely applied in a range from 490 to 780MPa TS. DP and TRIP-aided steels are strongly enhanced by an excellent El.
2) Cold rolled steel sheets are applied to body panels and structural parts. IF steels occupy the majority of steel sheets in body parts. With the increase in demand for high strength steel sheets, DP and TRIP-aided steel have gained strong interest and are actually applied also as hot rolled sheet steels.
3) Nb is a key element for the production of automotive steels due to various effects. For steels containing low temperature transformation products such as ferrite-bainite steel, DP steel and TRIP-aided steel, Nb works as an element controlling grain size and transformation behavior. For IF steels, Nb works as an element stabilizing interstitial solute C and N.

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