Development of High-Strength Hot-Rolled Sheet Products for Automobile Application

by

Shigeki Nomura / Asistant Manager of Product Development Sec., Kashima Steel Works
Yoshiaki Nakazawa / Staff of Product Development Sec., Kashima Steel Works
Shuji Nakai / Manager of Sheet Quality Control Sec., Kashima Steel Works
Nozomi Komatsubara / D. Phil., Manager of Steel Sheet Technology Dept., Tokyo Head Office
Youzou Hirose / Senior Research Engineer of Sheet Product Research Dept., Corporate R & D Lab.

Synopsis

The requirement to the steel industry for the supply of high-strength sheet products seems to be accelerated to reduce the car weight from the point of saving energy.

In this case stretch-flangebility is the most important parameter in order to meet the above requirement. At present the focuses of development are wheel discs, members and arms.

The authors have been developing much more formable high strength sheet products with a high stretch-flangebility. Metallurgical view points for these products were to reduce the amount of carbide particles and the hard second phase and to restrict the formation of the band structure. Those were achieved both by adjusting the chemical composition and by applying thermomechanical treatment through hot rolling. Basically that is the combination technology with higher finishing rolling temperature control and lower coiling temperature control. Formability could be further improved by increasing silicon content if the surface defect was solved, namely due to scale.

Now high strength hot-rolled sheet products over 540N/mm^2 *grade have been commercially accepted by automotive industry.*

1. Introduction

The worldwide trend of tightening the environmental protection has forced the automobile industry to reduce the weight of the production and increase the cooperative average fuel economy. As a result, the request for the steel industry to supply high-strength hot-rolled sheet steels with superior press-formability to the conventional high-strength steels is strengthening. The focuses of application to automotive use are wheel rims, wheel discs, members and arms. The points of development for application are listed in **Table 1**.

Flash butt or DC butt weldability is required for

Table 1 Points of development for application

Focus of application	Required properties	Metallurgical countermeasures
Wheel rims	•Flash butt or DC butt weldability	•To restrict too much hardening by adjusting the contents of titanium and columbium.
Wheel discs	•Stretch-flangebility •Good surface appearance	•To reduce the amount of carbide pariticles on grain boundary by lower coiling temperature.
Members, Arms	•Superior stretch-flangebility •Elongation	•To control microstructure by adjusting chemical compositions and by applying thermomechanical treatment through hot-rolling.

wheel rims application. That was obtained by adjusting titanium content and columbium content, which brought on precipitation hardening. Then softening and too much hardening of weld heat affected zone were restrained1),2).

The good stretch-flangebility and good surface appearance are required for wheel discs application. That was obtained by control of micro-structure of steel below 0.1wt% silicon content. Metallurgical view points for improving stretch-flangebility were to reduce the amount of carbide particles on the grain boundary by lower coiling temperature3).

For automotive under-body invisible parts as members and arms, superior formabilities are required. Those are good elongation and good stretch-flangebility. The authors have been developing the steels with superior formability ranging from 440 N/mm^2 to 780 N/mm^2 by adjusting the chemical composition and by applying thermomechanical treatment through hot-rolling. This paper describes the production process and metallurgical background of developed steels and describes mechanical properties compared with those of conventional steels4),5).

2. Material and Experimental Procedure

Four kinds of steels were vacuum-melted in an induction heating furnace. The chemical compositions are given in **Table 2**. Those were C-Mn steel, C-Mn-P steel, Nb-Ti steel and Si steel. The ingots were hot-forged to 50mm thick slabs. After heated at 1 473K, the steels were hot-rolled to 6mm thick. The finishing temperature of hot-rolling was 1 083K or 1 153K. Subsequently the coiling simulation was carried out by water-spray cooling at about 25K/s to the simulated coiling temperature ranging from 573K to 873K, and then cooled at 20K/h to room temperature.

Properties were investigated with 2mm thick specimens after removing the surface layers by machining. Tensile test was carried out with ASTM standard specimen. Stretch-flangebility was evaluated by the expansion ratio of the hole punched at 5% clearance. The hole expansion test was carried out with a cylindrical punch. The test was stopped at the crack just passing through the thickness. The hole expansion ratio, λ, was evaluated by the following equation;

$$\lambda = 100\mathrm{x}(D - D_0)/D_0(\%) \tag{1}$$

where D_0 and D are the initial and fractured diameters.

3. Results and Discussion

Tensile properties and hole expansion property are shown in **Fig. 1**. Relationships between tensile strength and elongation of developed steels were not clearly different from those of conventional steels, but H4(Si) steel had the best hole-expansion property, especially in case of higher finishing temperature. The H2(C-Mn-P) steel coiled at 873K had the worst hole-expansion property.

Effect of finishing temperature on microstructures of the steels coiled at 723K is shown in **Fig. 2**. Increase of carbon content caused increase of the second phase volume fraction. The band structure was formed in case of lower finishing temperature. The microstructure of H4(Si) steel, which had the best stretch-flangebility, contained dispersed second hard phase; fine pearlite or bainite, in the polygonal ferrite matrix.

Figure 3 shows micro-cracks observed in the break-parts of H2(C-Mn-P) steel coiled at 723K and at 873K after punching. The number of cracks of steel coiled at 873K was larger than that of the steel coiled at 723K. It was a reason of poor stretch-flangebility of the steel coiled at 873K. The sources of cracks were carbide particles and the cracks propagated along the boundaries between ferrite

Table 2 Chemical compositions of steels (wt%)

Steels	C	Si	Mn	P	S	sol. Al	N	Nb	Ti
H1 (C-Mn)	0.15	<0.01	1.43	0.016	<0.001	0.045	0.0031	<0.001	<0.001
H2 (C-Mn-P)	0.16	<0.01	1.42	0.061	0.001	0.036	0.0025	<0.001	<0.001
H3 (Nb-Ti)	0.08	<0.01	1.13	0.016	0.001	0.037	0.0027	0.024	0.018
H4 (Si)	0.10	0.57	1.14	0.015	<0.001	0.036	0.0023	<0.001	<0.001

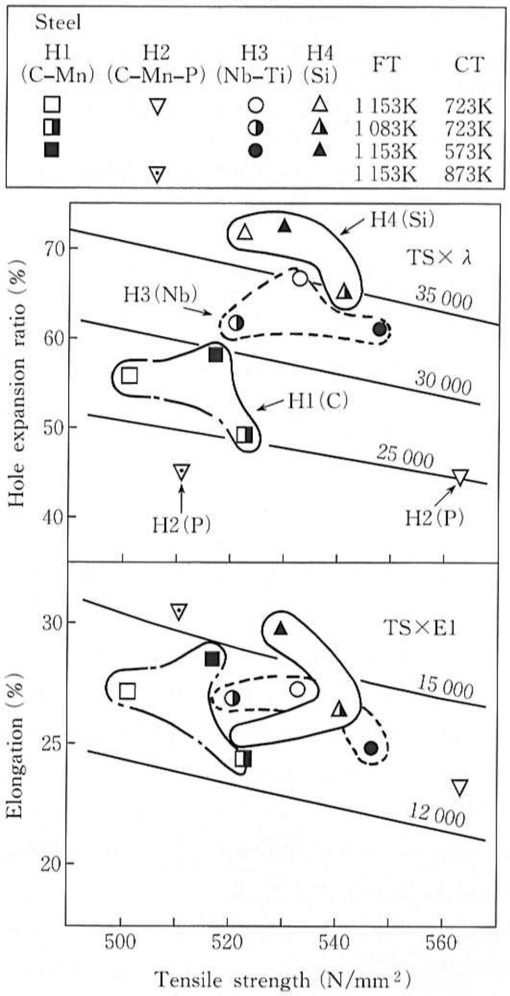


Fig. 1 Effect of rolling conditions and chemical compositions on tensile properties and hole expansion ratio

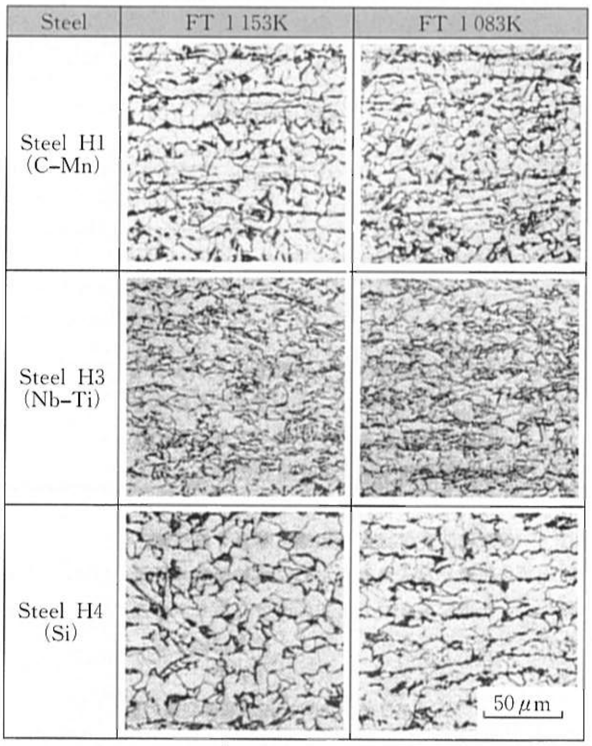


Fig. 2 Effect of finishing temperature on microstructures of steel H1(C-Mn), steel H3(Nb-Ti) and steel H4(Si)

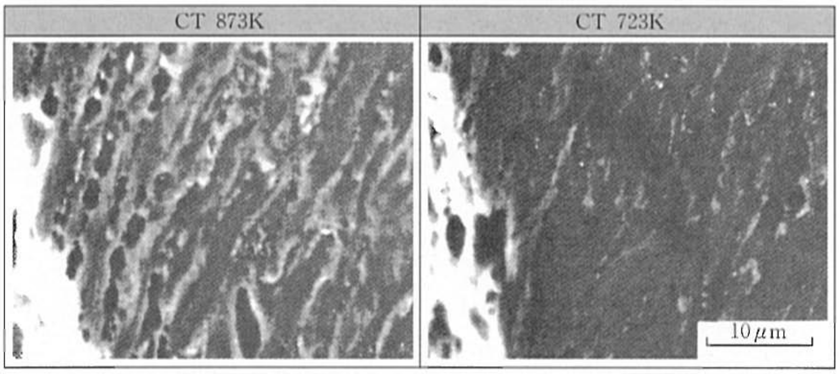


Fig. 3 Effect of coiling temperature on microstructures in break parts after punching of H2(C-Mn-P) steel

and hard phase.

The reasons of poor stretch-flangebility are grain boundary brittleness caused by precipitation of cementite particles on the grain boundary and by grain boundary segregation of phosphorus.

The points of improving stretch-flangebility are as follows: ①To restrain the defects occurrence during punching, ②To restrict the crack propagation during forming.

Steels with superior stretch-flangebility could been developed by metallurgical measures shown in **Table 3**.

Table 3 Metallurgical measures of improving stretch-flangebility

Viewpoint	Measure	Method
•Suppresion of microcrack's initiation at sheared edges of blanks. (Defects introduced during shearing.)	•Reduction of volume fraction of second hard phase. •Reduction of difference of hardness between second phase and matrix. etc.	•Reduction of carbon content and addition of silicon. •Avoidance of second hard phase such as martensite.
•Suppresion of crack propagation through improvement of ductility. (Crack propagation during secondary cold forming.)	•Dispersion of second phase. •Suppresion of grain boundary brittleness. etc.	•Employment of high temperature finishing and low temperature coiling. •Reduction of phosphorus content.
	•Increse in volume fraction of polygonal ferrite. etc.	•Addition of silicon. •Controlled cooling on hot-run table.

4. Commercial Production

4.1 Materials

Chemical compositions of developed steels and conventional steels are listed in **Table 4**. They were produced on the hot strip mill in Kashima Steel Works. Conventional steels were strengthen by precipitation of columbium and titanium and strengthen by transformation with increasing carbon content and manganese content.

Table 4 Chemical compositions of developed steels and conventional steels

Steels	Grade	C	Si	Mn	Others
Developed steels	440 N/mm^2	0.06	0.39	0.94	
	540 N/mm^2	0.07	0.84	1.51	
	690 N/mm^2	0.07	0.96	1.31	Ti, Cr
	780 N/mm^2	0.05	1.28	1.38	Ti, Cr
Conventional steels	440 N/mm^2	0.08	0.07	1.06	
	540 N/mm^2	0.14	0.05	1.34	
	540 N/mm^2	0.06	0.08	1.08	Nb, Ti
	590 N/mm^2	0.10	0.07	1.34	Nb, Ti

The volume fraction of hard phase of developed steel was reduced by decreasing carbon content below 0.07wt%. The silicon content of the steel was increased in order to enhance the formation of ductile polygonal ferrite and to reduce the difference in hardness between the ferrite matrix and the second phase. And titanium and chromium were added to the steels over 690 N/mm^2 grade for strengthening.

Higher finishing temperature was adopted in order to restrict the formation of band structure caused by non-recrystallization in the austenite region. And lower coiling temperature was adopted in order to reduce the precipitaion of cementite particles and the segregation of phosphorus on the grain boundary. Further controlled slow cooling in the ferrite forming region in order to form a large amount of ductile polygonal ferrite.

Production condition of 780 N/mm^2 grade developed steel is shown in **Table 5**, and optical microstructure is shown in **Fig. 4**.

Although higher finishing temperature, which would impede formation of polygonal ferrite, was adopted for accelerating recrystallization, the microstructure consisted of a large amount of polygonal ferrite and bainite because of adjusting chemical composition and controlling cooling.

Table 5 Production condition of 780 N/mm^2 grade developed steel

Reheating temperature	Finishing temperature	Coiling temperature
1 561K	1 188K	708K

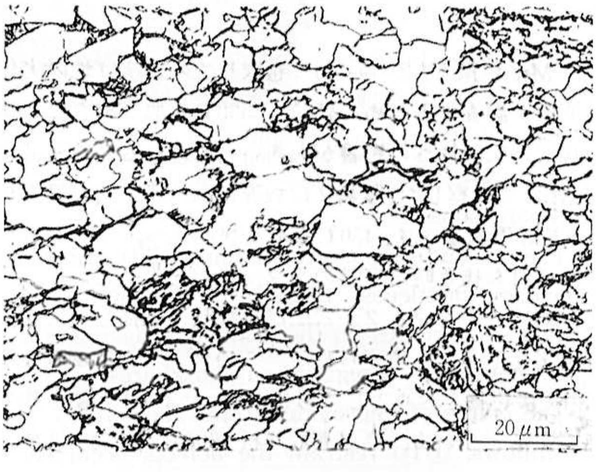


Fig. 4 Optical microstructure of 780 N/mm^2 grade developed steel

4.2 Tensile Properties and Stretch-Flangebility

Tensile test was carried out with a JIS No.5 specimen along rolling direction. Tensile properties were shown in **Fig. 5**. The ratio of yield strength and tensile strength was about 0.75, which was similar value to that of conventional steels. Elongation was superior to that of conventional steels for a large amount of ductile polygonal ferrite.

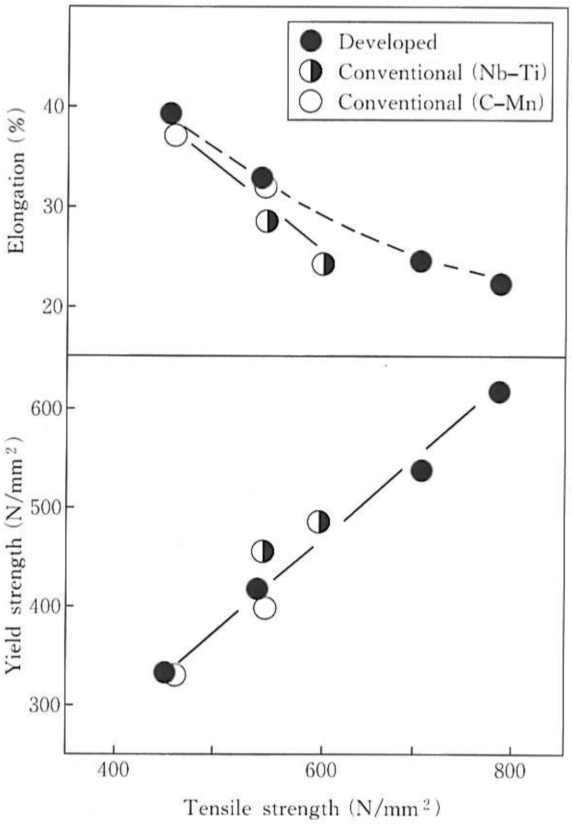


Fig. 5 Relationship between hole expansion ratio with a cylindrical punch and tensile strength

The relationship between tensile strength and stretch-flangebility is shown in **Fig. 6**. Stretch-flangebility was evaluated by 20% clearance punched hole-expansion ratio with a cylindrical punch. Developed steels had superior stretch-flangebility to conventional steels. 780N/mm^2 grade developed steel had 540N/mm^2 grade stretch-flangebility of conventional steel. Appearance of sheared edge of 540 N/mm^2 developed steel is shown in **Fig. 7** compared with that of columbium bearing steel. The developed steel reflected smooth shape, but the columbium bearing steel reflected creviced shape by micro-cracks joining.

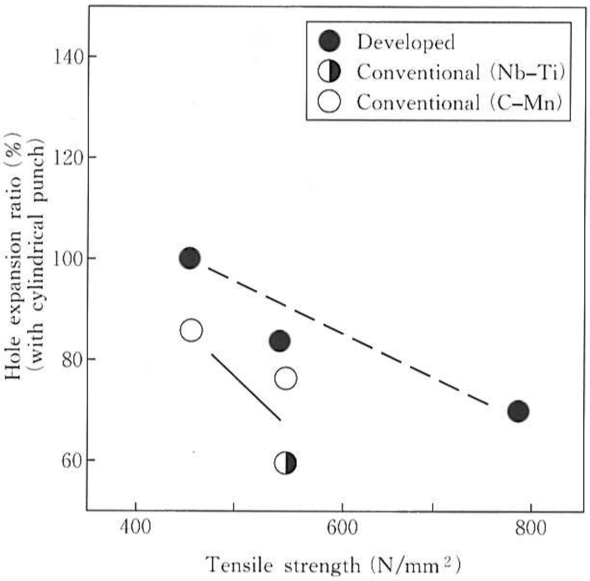
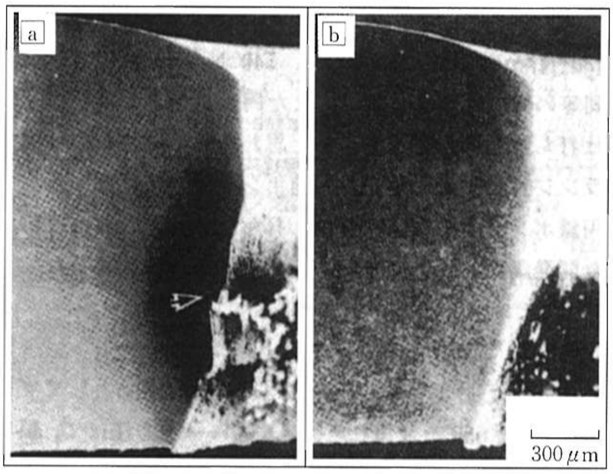


Fig. 6 Relationship between hole expansion ratio with a conical punch and tensile strength



(a) : Conventional steel (Columbium bearing steel)

(b) : Developed steel

Fig. 7 Appearance of sheared edge after punching of developed steel and conventional columbium bearing steel

4.3 Hole-Expansion Property

Hole-expansion property was evaluated by the expansion test with a conical punch. That was investigated by 13% clearance punched 12mm hole-expansion test. The relationship between tensile strength and hole expansion ratio is shown in **Fig. 8**. Developed steels had superior hole expansion property to conventional steels.

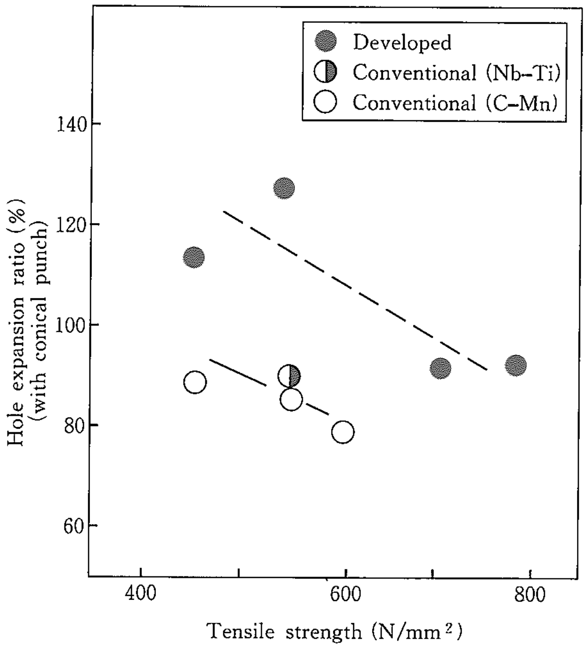


Fig. 8 Relationship between hole expansion ratio with a conical punch and tensile strength

4.4 Drawability

The method of cylindrical cup drawing test is shown in **Fig. 9**. Relationship between limit drawing ratio (LDR) and tensile strength is shown in **Fig. 10**.

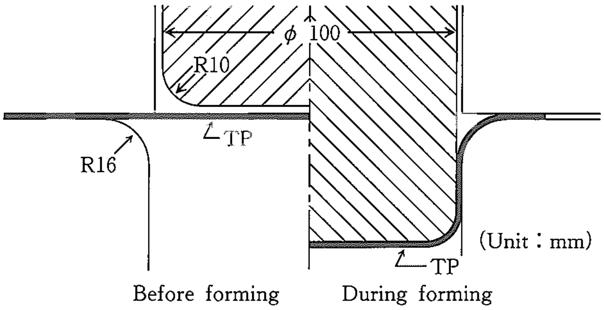


Fig. 9 Cylindrical cup drawing testing method

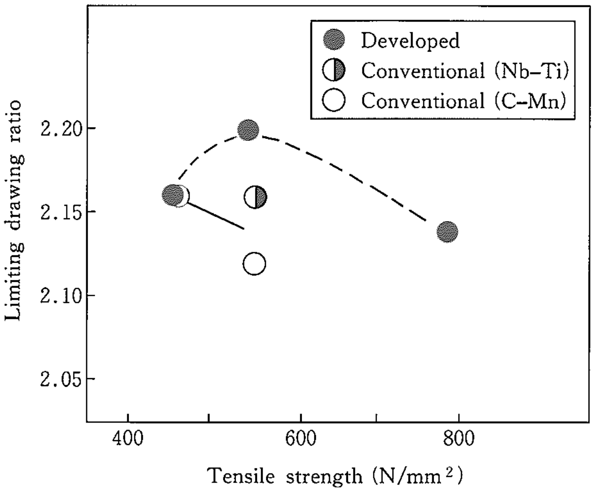


Fig. 10 Relationship between limiting drawing ratio and tensile strength

Developed steels had superior LDR to conventional steels. It was considered that the rankford value of developed steel was higher because of random texture caused by higher finishing temperature for accelerating austenite recrystallization.

4.5 Stretchbility

The test for evaluation of stretchbility was carried out as shown **Fig. 11**. The relationship between tensile strength and limit dome height (LDH) in case of plane strain is shown in **Fig. 12**. Developed steels had good LDH property. It was considered that developed steels contained a large amount of ductile polygonal ferrite therefore had higher n values because of favorite microstructure for elongation.

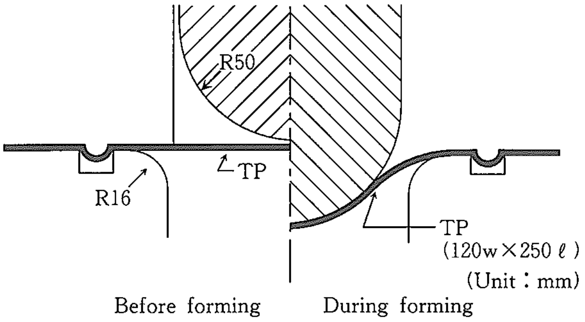


Fig. 11 Testing method for limiting dome height

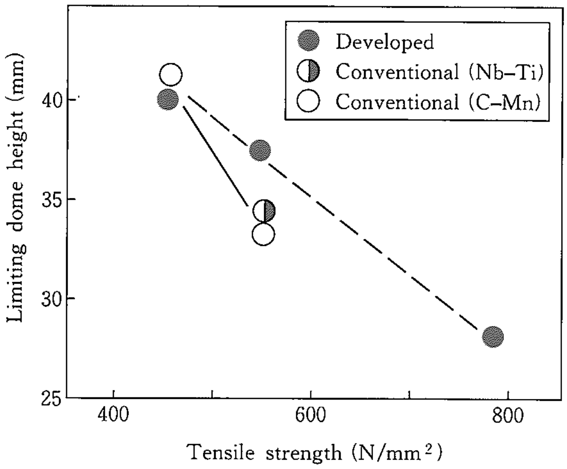


Fig. 12 Relationship between limiting dome height and tensile strength

4.6 Fatigue Property

Not only formability but also fatigue property is important. Fatigue test was carried out with a JIS No.1-20 specimen. Type of test was plane bending and frequency was 25Hz. And stress ratio was -1.0.

The relationship between tensile strength and fatigue limit is shown in **Fig. 13**. Increase of the tensile strength led to increase of fatigue limit. However the ratio between fatigue limit and tensile strength of developed steel was higher than that of conventional steel. It was considered that ferrite matrix of developed steel, which was weak for fatigue, was strengthen by silicon solid solution[6]. The ratio between fatigue limit and tensile strength was 0.45 for the conventional steel and 0.50 for the developed steel.

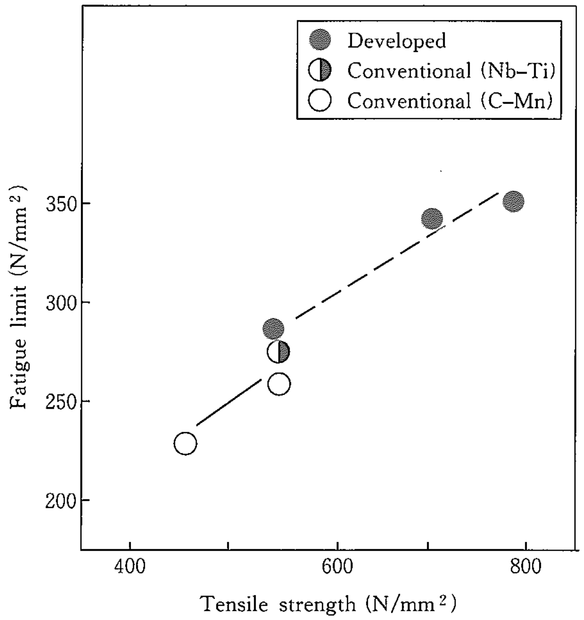


Fig. 13 Relationship between fatigue limit and tensile strength

5. Summary

Tensile properties and hole expansion ratio of developed steels are shown in **Fig. 14** compared with those of conventional steels, dual phase steels[7),8)], TRIP (Transformation Induced Plasticity) steels[9),10)] and bainite steels[11)].

Elongation of developed steel is equal to dual phase steel following TRIP steel. Hole expansion limit of developed steel is equal to bainite steel. Consequently developed steels have a good combination of elongation and hole expansion limit.

Comparison in various properties between 540 N/mm² grade developed steel and 540 N/mm² grade conventional steels is shown **Fig. 15**. As above developed steel has superior properties, ductility, stretch-flangebility, hole expansion limit, drawability, stretchbility and fatigue property, to conventional steels.

Developed steels ranging from 440 N/mm² to 780 N/mm² can be commercially offered according to a request of automotive industry.

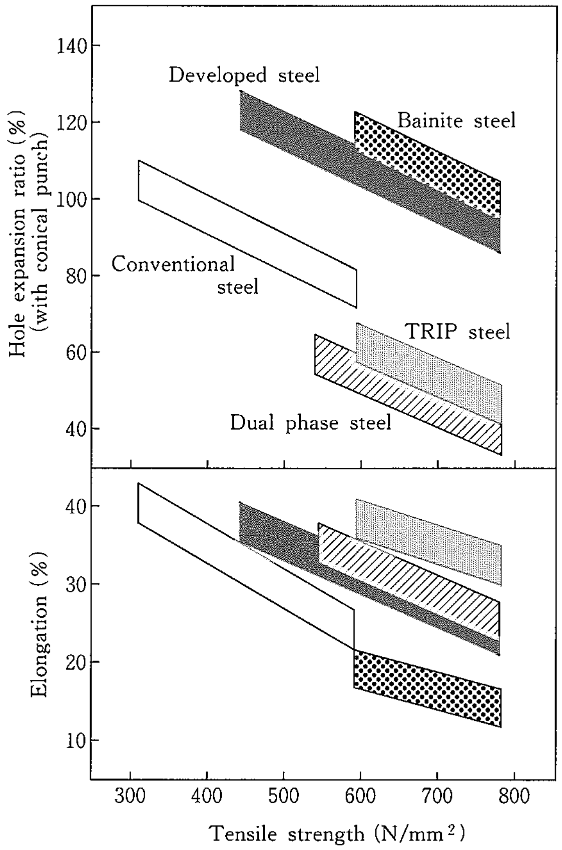


Fig. 14 Tensile properties and hole expansion ratio of various types of steels

6. Conclusion

Hot-rolled high strength steels ranging from 440 N/mm² to 780 N/mm² with superior formability have been developed. The production points of these developed steels are as follows:

(1) The points of development of shear-edge stretch-flangebility are to restrict generation of crack and to restrain propagation of crack during punching. So it is important to reduce the volume fraction of hard phase and to restrict the formation of band structure. Further it is necessary to suppress the segregation of phosphorus on grain boundary and to restrain the precipitation of the large cementite particles on grain boundary.

(2) Based on above metallurgical points, the superior formable steels ranging from 440 N/mm² to 780 N/mm² are developed by decreasing carbon content and increasing silicon content and by means of

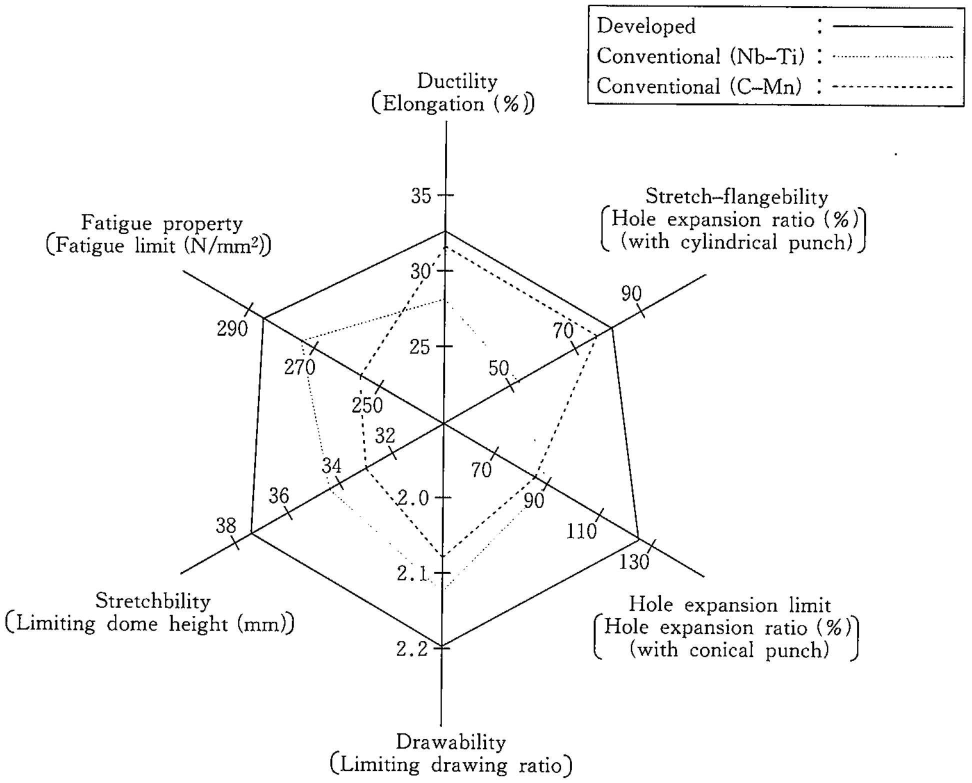


Fig. 15 Comparison in various properties between 540 N/mm^2 grade developed steel and 540 N/mm^2 grade conventional steels

lower coiling temperature, higher finishing temperature and controlling cooling.

(3) Developed steels have good drawability. It seemed to be caused by isotropic high rankford value by means of higher finishing temperature.

(4) Developed steels have good elongation and stretchbility. It caused by large amount of ductile polygonal ferrite obtained by adjusting chemical compositions and controlling cooling.

(5) Developed steels have good fatigue property caused by ferrite strengthen by silicon solid solution.

Shigeki Nomura

Asistant Manager of Product
Development Sec.,
Kashima Steel Works

Phone: 0299(84)2558

References

1) S. Hashimoto, S.Kambe, M.Sudo and Y.Tsugami : SAE Paper No.820283
2) N.Yamauchi, K.Kunishige, T.Taka and N.Nagao : Tetsu-to-Hagane, **68** (1982), p.295
3) N.Nagao, K.Kunishige snd S.Hamamatsu : SAE Paper No.840012
4) N.Nomura, Y.Hirose, N.Komatsubara, K.Kunishige, H. Fukuyama and S.Nakai : CAMP-ISIJ, **5** (1992), p.1851
5) H.Fukuyama, S.Katsu, S.Nakai Y.Hirose, N.Nomura, N. Komatsubara and C.Sudo :CAMP-ISIJ, **5** (1992), p.1885
6) M.Kurita and K.Toyama : CAMP-ISIJ, **5** (1992), p.1891
7) S.Sugisawa, S.Hamamatsu, K.Kikuchi and K.Kunishige : Tetsu-to-Hagane, **68** (1982), p.130
8) K.Kunishige, M.Takahashi, S.Sugisawa and S. Hamamatsu : Sumitomo-Kinzoku, **33** (1981), p.39
9) Y.Sakuma, N.Kimura, A.Itamai, S.Hiwatashi, O. Kawano and K.Sakata : Sinnitetu-Giho, **354** (1994), p.17
10) S.Nomura, N.Komatsubara, K.Kunishige and N.Mizui : CAMP-ISIJ, **5** (1992), p.149
11) O.Kawano, K.Easaka, S.Kato, H.Abe, J.Wakita, M.Takahashi, M.Katayama and S.Harada : Seitetsu-Kenkyu, **329** (1988), p.15