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MATERIAL DESIGN OF 690-780 MPA GRADE HOT-ROLLED SHEET STEELS FOR WHEEL USE

Hirohisa Kikuchi[1], Norio Imai[2], Toshiro Tomida[2],
Kiyoyuki Fukui[3], Shigeki Nomura1[3], Shin-ichirou Katsu[3]

Sumitomo Metal Industries, Ltd.
[1]Kashima Steel Works
3, Hikari, Kashima, Ibaraki 314-0014, Japan
Sumitomo Metal Industries, Ltd.
[2] Corporate Research & Development Laboratories
1-8, Fusocho, Amagasaki, Hyogo 660-0891, Japan
Sumitomo Metal Industries, Ltd.
[3]Tokyo Head Office
8-11, Harumi 1-chome, Chuo-ku, Tokyo 104-6111, Japan

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Abstract

Hot-rolled sheet steels of a low Si composition strengthened by the addition of Ti and Nb have been investigated to develop 690 to 780 MPa grade materials for wheel disks and rims. The hot-rolled sheet steels of 0.09%C-0.06%Si-1.5%Mn base composition with various concentrations of Ti and Nb were prepared in the laboratory under various post-rolling cooling conditions. Then the influence of microstructures and microalloying of Ti and Nb on mechanical properties were investigated. It has been found that the steels with a mixed structure consisting of ferrite and bainite show superior hole expandability, while the steels with ferrite and pearlite microstructures have better elongation. In these steels, the addition of Ti and Nb effectively increased their tensile strength, and the strength over 700 MPa was attained when 0.1% of Ti and 0.04% of Nb were alloyed with them. Based on the results, 690 to 780 MPa grade hot-rolled sheet steels for wheel disks and rims were manufactured on trial using a Ti- and Nb-added low-C low-Si composition and controlling their microstructures by post-rolling cooling. The developed steels successfully met the requirements for wheel disks and rims.

Introduction

Many requirements other than ordinary mechanical properties are met with high strength hot-rolled sheet steels for automotive chassis parts such as wheels and suspension arms. In the case of wheels, large hole expandability and high fatigue strength properties are required from the material to prevent deficient forming of hub holes [1-3] and to ensure a long life of wheels [3]. Furthermore, DC butt weldability and formability of welded joints are major material concerns for wheel rims. In general, the larger the strength becomes, the more difficult it becomes to fulfill all of those requirements. Therefore, understanding of the influence of strengthening mechanisms on those properties are of great importance to develop such high strength sheet steel. At present, hot-rolled sheet steels up to 590 MPa in tensile strength are mainly used as the material for wheels, and the production of 780 MPa grade steels for this application is gradually increasing. Among the hardening mechanisms such as solid solution, precipitation and transformation hardening, it is known that the addition of Si as a solute in ferrite is quite effective for better press formability [4], while the addition of Si and/or carbonitride-forming elements of Ti and Nb are known to be beneficial to obtaining superior fatigue strength [3]. However, Si is disadvantageous as an additive in wheel materials. It tends to cause a surface defect, the so-called tiger scale [5-6] and degrades the surface appearance of products. Therefore, in this study, a low Si composition was chosen as a base composition, and strengthening by microalloying of Ti and Nb was investigated to develop 690 to 780 MPa grade hot-rolled sheet steels for wheels. Another point that has been taken into account here is to manufacture two kinds of steel suited for disks and rims using a single chemical composition. Since the requirements for these steels are somewhat different, different compositions are usually used. Hence, if it is possible to manufacture these steels using slabs of the same composition, it may reduce production cost. In this article, the laboratory results on effects of Ti and Nb as well as process conditions on various properties of steels are firstly presented. Then the trial production of hot-rolled sheet steels using a commercial rolling mill is described.

Fundamental Study

Experimental Procedure

Table I lists the chemical compositions of the steels used in this study. The contents of Ti and Nb being precipitation-hardening elements were varied. These steels were remelted in a vacuum furnace and the resultant ingots were forged and hot-rolled as illustrated in Figure 1. The slabs were heated to 1200°C and hot-rolled with a finishing temperature of 840°C. Then they were water-cooled at a rate of about 20°C/s to 670°C, air-cooled for 3 to 7 s, and again water-cooled to coiling temperatures (CT) ranging from 580°C to the room temperature. They were then furnace-cooled at a rate of 20°C/h to the room temperature. For these steels, tensile properties and the hole expansion limit were investigated.

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

C	Si	Mn	P	S	Ti	Nb
0.09	0.06	1.44	0.012	<0.001	0.02-0.10	tr.-0.04

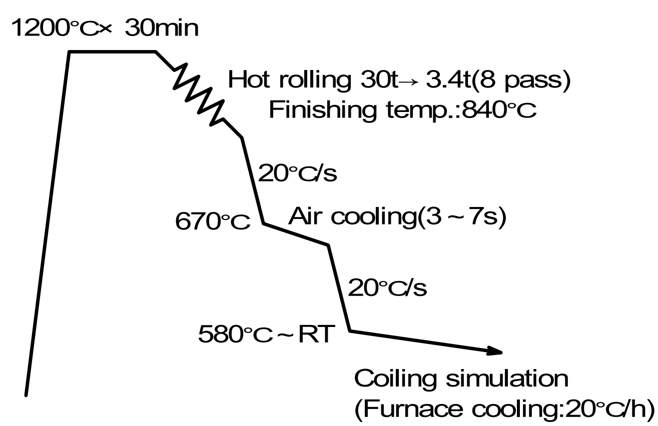

Figure 1. Hot rolling simulation.

Effects of Ti, Nb and Microstructure on Mechanical Properties

As shown in Figure 2, the microstructures of hot bands were largely dependent on the coiling temperature. The primary structures of hot bands coiled at 580°C, 450°C and room temperature were a mixture of ferrite (F) and pearlite (P), ferrite and bainite (B) and ferrite and martensite (M), respectively.

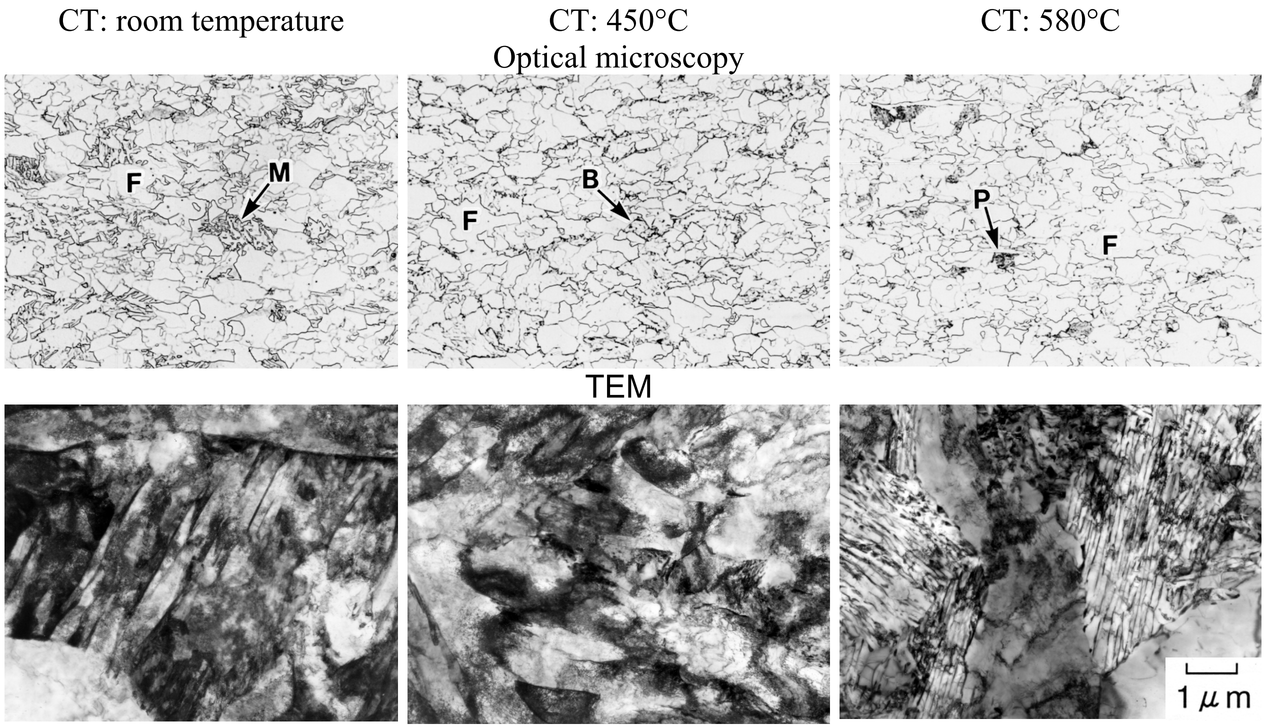

Figure 2. Effect of coiling temperature on microstructure of 0.06%Ti-0.04%Nb steel.

Figure 3 shows the balance between tensile strength (TS) and elongation (EL) and that between tensile strength and hole expansion limit (HEL). The tensile strength was maximum for coiling at room temperature, where the microstructure consisted of ferrite and martensite. Although the value of elongation decreased due to the increase in tensile strength, a good balance between strength and elongation was attained because of the existence of martensite as a second phase, which is known to increase the work hardening rate [7]. However, this steel with ferrite and martensite has an inferior hole expandability. It showed a small hole expansion limit of 30 to 40 %. On the other hand, the hole expansion limit showed a maximum of 70 to 100 % at a coiling temperature of 450°C. This means that the hot band with a ferrite and bainite duplex structure has a superior hole expandability and is best suited to the use for disks. The hot band with a ferrite and pearlite duplex structure that was obtained at the highest coiling temperature of 580 °C also showed a good balance between strength and elongation, whereas it exhibited an inferior hole expandability as was the case with the steel with ferrite and martensite. Therefore, as far as the balance between strength and elongation is concerned, both steels with the ferrite/pearlite and ferrite/martensite structures may be suited to be used for rims, in which the material undergoes severe flare forming. However, in this research, the steels with a ferrite and pearlite duplex structure were chosen for further investigation, since it would exhibit a better DC-butt weldability that was another requirement on the material for rims. This point will be explained in the next section. The effects of Ti and Nb addition on tensile strength are shown in Figure 4. Tensile strength increased with increasing Ti concentration regardless of coiling temperature. The increase in Nb concentration also increased tensile strength. However, it only occurred when the coiling temperature was above 450°C and the Ti concentration was less than 0.06 mass %.

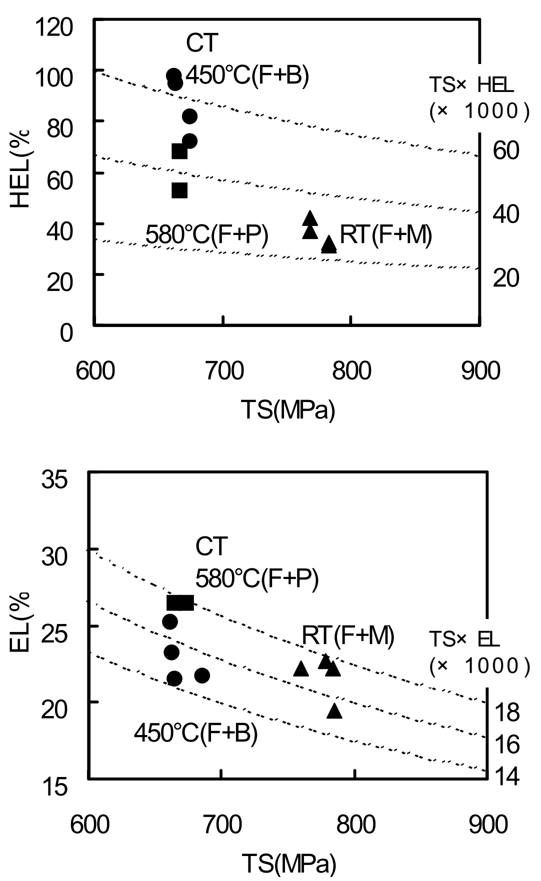

Figure 3. Effect of coiling temperature on tensile properties and hole expansion limit.

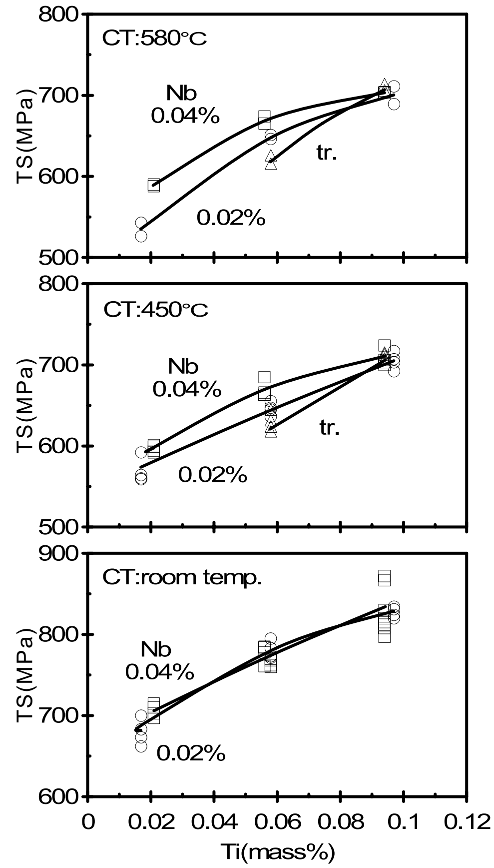

Figure 4. Effect of Ti and Nb on tensile strength.

Trial Production and Performance for Wheels

Steels for Disks

Formability

Based on the laboratory results, two Ti- and Nb-added low-C low-Si sheet steels of 690 and 780 MPa grades of 2.9 mm in thickness were produced for disks on trial in Sumitomo's commercial mill. In Table II the chemical compositions of these steels are listed. Figure 5 shows the balance between tensile strength and elongation and that between tensile strength and hole expansion limit in the steels, compared with those of conventional steels of lower strength. The trial steels show the total elongation of about 20 % and the hole expansion limit of about 70 %, and hence, they would have sufficient formability for disk press forming. This is because the formation of ferrite has been promoted and an extremely fine-grained microstructure has been obtained by controlled rolling and cooling as shown in Figure 6.

Table II. Chemical compositions of trial steels used disk (mass %).

TS(MPa)	C	Si	Mn	P	S	other
690	0.08	<0.1	1.47	<0.02	<0.001	Ti,Nb
780	0.07	<0.1	1.46	<0.02	<0.001	Cr,Ti,Nb

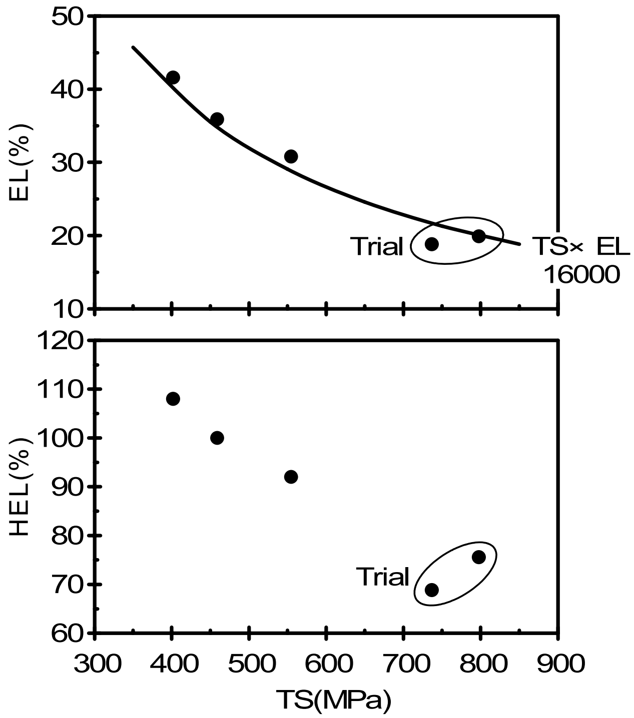

Figure 5. Tensile strength vs. elongation and tensile strength vs. hole expansion limit.

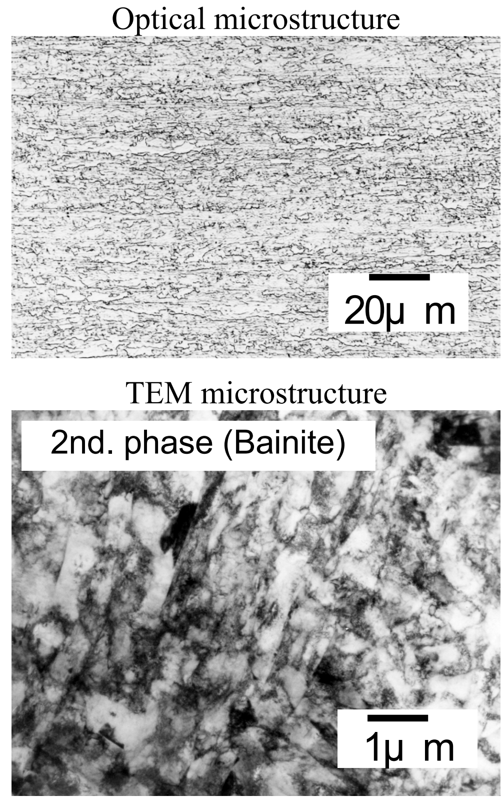

Figure 6. Microstructure of trial 780 MPa steel.

Fatigue Toughness

In order to estimate the fatigue toughness when used in actual wheels, a disk was made using the trial steel and, after assembling it to a wheel with a rim, a rotation vending fatigue test was carried out [8]. The condition of disk press forming used at the above disk production was the same as that usually applied in the disk production using conventional 540 MPa grade sheet steel despite the difference in tensile strength. Fatigue cracks, as shown in Figure 7, mainly occurred at the hat top of the rear side of the disk and propagated to the direction of circumference. Fatigue life of the actual wheel is shown in Figure 8. With increasing tensile strength, the fatigue life of wheels both with and without ventilation holes increased, but it tended to saturate above a tensile strength of 700 MPa. Then, to see if residual stresses by press forming influence fatigue life, plain bending fatigue tests were also made using small test pieces cut from the trial and conventional steel sheets, and the fatigue life without residual stresses was estimated from measured S-N curves. As shown in Figure 9, fatigue life of the test pieces did not saturate up to a tensile strength of 800 MPa. It is thus likely that the lower fatigue life of actual wheels is caused by the residual stress in tension due to press forming. If the shape of the disk is adjusted and the residual stress is reduced, the trial steel should show a longer fatigue life in an actual use.

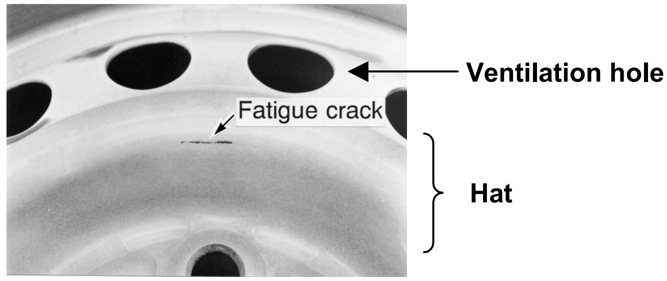

Figure 7. Fatigue crack in wheel disk.

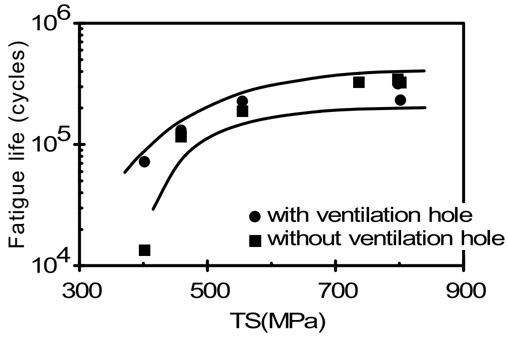

Figure 8. Effect of tensile strength of steel on fatigue life of wheels.

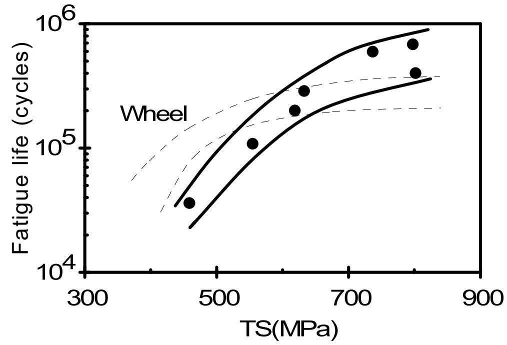

Figure 9. Effect of tensile strength of steel on fatigue life of test specimens.

Steels for Rims

Three sheet steels of 690 and 780 MPa tensile strength and 2.3 mm thickness were test-produced in Sumitomo's commercial mill. In Table III, chemical compositions of these sheet steels are listed. Steel A and steel B of 690 MPa and 780 MPa grades are mainly strengthened by Ti and Nb added as precipitation-hardening elements. Steel C being a 780 MPa grade is mostly strengthened by Cr and Mo added as a transformation-hardening agent.

Table 3. Chemical compositions of trial steels used rim (mass %).

Steel	TS(MPa)	C	Si	Mn	P	S	other
A	690	0.08	<0.1	1.55	<0.02	<0.001	Ti,Nb
B	780	0.11	0.4	1.57	<0.02	<0.001	Cr,Ti,Nb
C	780	0.10	0.4	1.49	<0.02	<0.001	Cr,MoNb

Since flare formability of materials including welded joints was one of key factors to be considered for rims as mentioned before, flare forming was first simulated. The rims that were trimmed after DC butt-welding were flare-formed until breakage occurred as illustrated in Figure 10. The rims were expanded from the side with a conical punch with a vertex angle of 60 degrees, and the flare expansion limit is defined as the ratio of the increase in diameter to the initial diameter was measured. The breakage by flare expansion occurred at the heat affected zones near the weld joints. The results are shown in Figure 11 as a function of the difference in Vickers hardness between base metal and heat-affected zones, ΔHV, and as a function of elongation (measured by tensile tests). It is seen in this figure that the flare expansion limit has decreased with increase in ΔHV. There was no obvious relation between the flare expansion limit and the elongation. Thus it was found important to choose the low C composition with additions of Ti and Nb like Steel A and to reduce the concentration of transformation hardening elements such as Mo and Cr to the utmost.

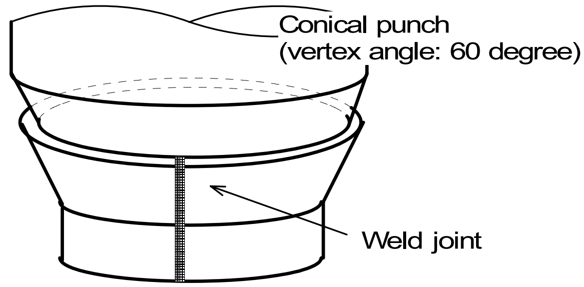

Figure 10. Flare-forming simulation with conical punch.

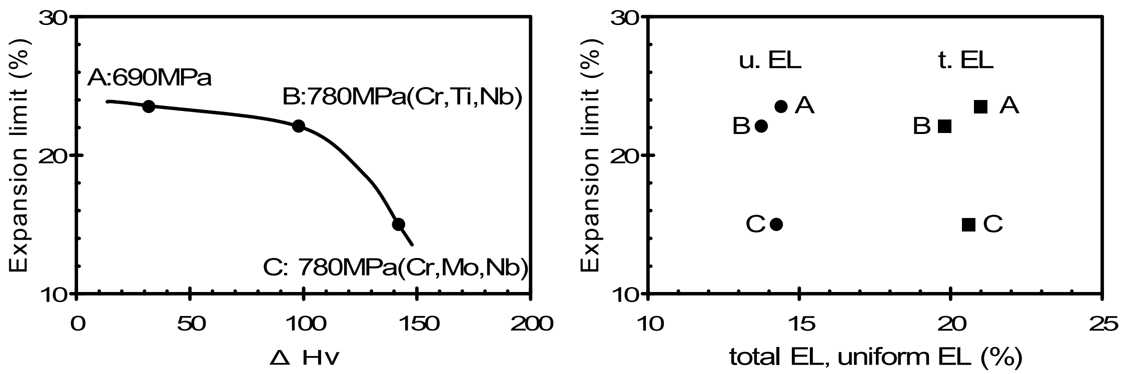

Figure 11. Effect of elongation of steel (total EL and uniform EL) and the difference of Vickers hardness between heat affected zones and base metal on the expansion limit in flare-forming.

Production of Steels for Disks and Rims using a Single Chemical Composition

According to the above results, one might expect that it may be possible to manufacture the two kinds of steel for disks and rims using a single chemical composition by alteration of post-rolling conditions (compare the composition in the third row in Table II and that of Steel B in Table III). Hence we tried to manufacture 780 MPa grade sheet steels of 2.9 mm in thickness for disks and rims using slabs of the same composition. The chemical composition of slabs and hot-rolling conditions used are listed in Tables IV and V. Figure 12 shows the balance between tensile strength and elongation and that between tensile strength and hole expansion limit of the steels. It is seen that both steels have enough strength for the 780 MPa grade and the change in post-rolling conditions has successfully altered their formability. The higher coiling temperature has resulted in the better elongation of about 16 to 20 %, being suited to the use for rims, while the lower coiling temperature has led to the larger expansion limit of about 50 to 80 %, being suited to disks.

Table IV. Chemical composition of trial steels for both disks and rims (mass %).

C	Si	Mn	P	S	other
0.09	0.02	1.5	<0.02	<0.001	Ti,Nb,Cr

Table V. Hot rolling conditions of trial steels.

	Finishing temperature (°C)	Coiling temperature (°C)
Rim use	840 - 900	>500
Disc use		<500

Then a DC butt-welding test was carried out for the steel rims and the change in hardness in the heat-affected zones was investigated to determine if it had sufficient flare formability. In Figure 13, the hardness distributions across welded joints for the developed steel as well as for a conventional 590 MPa grade steel are presented. The developed steel showed much smaller variation in hardness than the conventional steel, indicating the superior flare formability. The ΔHv of the developed steel is only about 30 that would correspond to a flare expansion limit over 20 % according to the data shown in Figure 11. Therefore, the two kinds of steel for disks and rims can be produced using an identical low-C and low-Si composition to which proper amounts of Ti and Nb are added and by controlling process conditions to attain suitable microstructures.

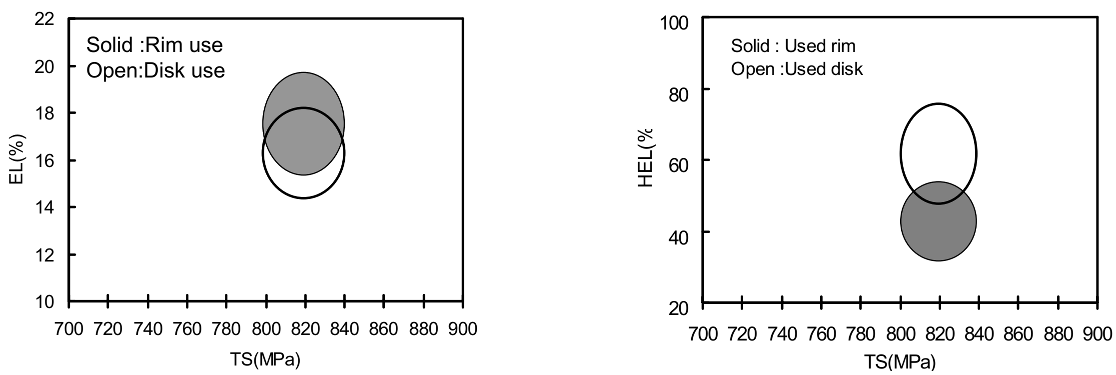

Figure 12. Tensile strength vs. elongation and tensile strength vs. hole expansion limit.

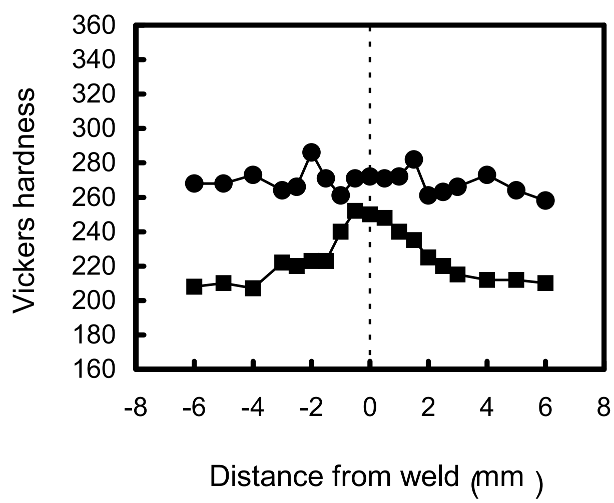

Figure 13. Comparison of the distribution of hardness between trial 780 MPa grade steel and conventional 590 MPa grade steel.

Conclusions

To develop 690 to 780 MPa grade hot-rolled sheet steels for car wheels, effects of microalloying of Ti and Nb into low C and low Si compositions as well as hot-rolling conditions on various properties have been studied. Then the trial production of sheet steel based on the laboratory study was carried out and the developed steels were applied to wheels. This investigation has led us to following conclusions:

(1) It has been found that the steel consisting of ferrite and bainite obtained at a coiling temperature around 450 °C shows a superior hole expandability and is best suited to the use for wheel disks in the materials under investigation.

(2) The steels with ferrite/pearlite and ferrite/martensite duplex phase structures show a good balance between strength and elongation, although they exhibit inferior hole expandability. With DC-butt weldability being taken into account, the former steel is suitable to the use for wheel rims.

(3) The addition of Nb effectively increases tensile strength of steels as the coiling temperature is above 450 °C and the Ti concentration is less than 0.06 mass %.

(4) The steels of 690 and 780 MPa strength test-produced using Sumitomo's commercial mill, of which the microstructure has been controlled to be a ferrite and bainite duplex structure for disks, have shown superior hole expandability as expected. The application of the steels to actual wheels has confirmed that they have sufficient formability for disk press forming and superior fatigue toughness necessary for a long wheel life.

(5) The test-produced steels in the same strength range, of which microstructure has been controlled to be a ferrite /pearlite duplex structure for rims, have expectedly good ductility and DC butt weldability. Particularly, a smaller variation in hardness in welded joints was shown and thereby, they exhibited a superior flare formability.

(6) It has been also confirmed by test production that the two kinds of high strength hot-rolled sheet steels suited to wheel disks and rims can be manufactured using a single Ti- and Nb-added low-C low-Si composition by controlling microstructures.

References

1) A. Wimmer and J. Petersen: SAE Paper No.790713, (1979).

2) M. Kurita, M. Yamamoto, K. Toyama, S. Nomura and K. Kunishige: ISIJ Int., 36(1996), 481.

3) K. Toyama and M. Kurita: Impact of Improved Material Quality on Properties, Product Performance, and Design ASME, MD28 (1991), 185.

4) R. G. Davies and C. L. Magee: Proceedings AIME Annual Meeting, (1979), 7.

5) T. Fukagawa, H. Okada and Y. Maehara: ISIJ Int., 34(1994), 906.

6) H. Okada, T. Fukagawa, H. Ishihara, A. Okamoto, M. Azuma and Y. Maeda: ISIJ Int., 35(1995), 906.

7) T. Furukawa, H. Morikawa, H. Takechi and K. Koyama: Proceedings AIME Annual Meeting, (1979), 294.

8) M. Kurita, N. Komatsubara, K. Asano, M. Sano, Y. Nakazawa and M. Yamamoto: Proceedings JSAE Annual Congress, 961(1996), 327.