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High Strength Hot-rolled Steel Sheets for Automobiles

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Abstract

Large weight reduction by application of high strength steels to underbody parts can be expected since relatively thick sheets are now adopted. In this paper, several different approaches to improve press formability of high strength hot rolled steels are explained. The basic concept of mechanical property control and the performances of a couple of high strength hot rolled steels, which have been developed at Nippon Steel Corporation, are given.

1. Introduction

There is an increasing demand for fuel consumption and the reduction of CO_2 emissions of automobiles from the viewpoint of the environment. Weight reduction of auto-bodies has been promoted as well as an improvement of engine efficiency, reduction of friction and so on. Hot-rolled steel sheets are used for chassis and underbody components that account for 25% or so of the total weight of a car body, and for some structural components, to which crashworthiness is required. Since relatively thick sheets are used for these components, considerable weight reductions are expected. Because safety is a major concern for the chassis, high durability and reliability are required as well as good press formability to their complicated shapes. This seems to be the reason why a gauge down of these components is less progressive than other parts, as is well known for exposed panels. The application of hot rolled high-strength steel sheets to the chassis components, which leads to considerable weight reduction, is expected to expand rapidly in the coming years. It is, therefore, demanded to develop as hot rolled high-strength steel sheets with good press formability and fatigue strength.

In this paper, the performances and metallurgical routes of typical as hot rolled high-strength steel sheets developed at Nippon Steel Corporation will be discussed.

2. Hot-rolled Steel Sheets Containing Retained Austenite

Press formability is the key factor to adopt higher strength steels, and elongation is considered to be the most appropriate mechanical property to express the press formability of high strength steels. Hot-rolled steel sheets containing retained austenite (low-alloy TRIP type multi-phase steels; hereinafter referred to as low alloy TRIP steels) are high-strength steel sheets having large elongation. This large elongation, especially a large uniform elongation, is the result of a so called transformation-induced plasticity (TRIP) effect wherein strain concentration is avoided as a result of the transformation of retained austenite to hard martensite during press forming[1, 2].

Fig. 1 shows the effect of the volume fraction of retained austenite on the mechanical properties of steels[3]. The product of the strength TS and total elongation T.El of low alloy TRIP steels increases with the amount of retained austenite, whereas the product of TS and the local elongation L.El show little changes. It is, therefore, understood that the increase in total elongation is due to the increase in uniform elongation. The higher the stability of retained austenite which can be assessed as the amount of transformation of retained austenite during tensile deformation, the larger TS × T.El product can be obtained, as shown in **Fig. 2**[4]. It can therefore be concluded that the elongation of low alloy TRIP steels is governed not only by the amount of retained austenite but also by its stability. The basic metallurgical concept to control the microstructure of low alloy TRIP steels and examples of mill scale production with performances such as weldability and fatigue properties.

2.1 Basic metallurgical concept to control the microstructure of hot-rolled steel sheets containing retained austenite

In order to obtain enough retained austenite at an ambient temperature in steel without adding large amount of austenite former

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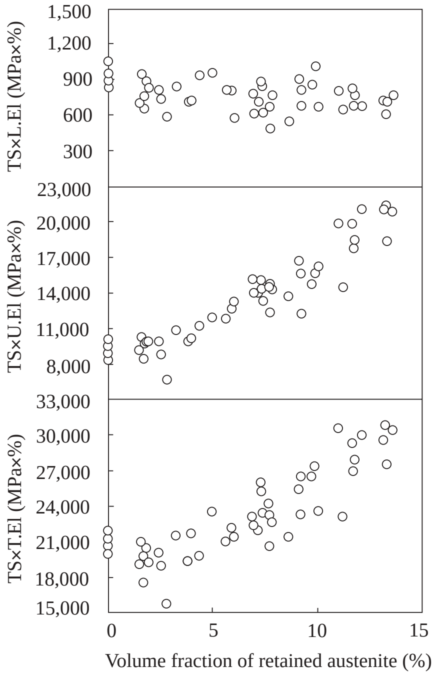

Fig. 1 Effect of the amount of retained austenite on strength-elongation combination of low alloy TRIP steels (T.El: total elongation, U.El: uniform elongation, L.El: local elongation)

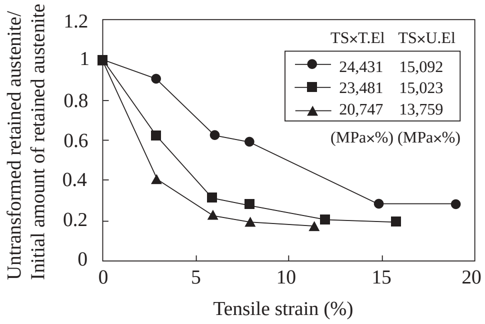

Fig. 2 Change in volume fraction of retained austenite as a function of tensile strain and the effect of stability of retained austenite on the strength-elongation combinations

elements such as Mn and Ni, it is necessary to enrich C to untransformed austenite for lowering the martensite transformation start temperature (M_S temperature) of the austenite. As a result, the final microstructure consists of ferrite as the main phase, bainite, and retained austenite. **Fig. 3** shows an example of the microstructure. In order to obtain this microstructure in an actual production line, the following two transformation phenomena are used.

(1) Ferrite transformation: As ferrite transformation proceeds, carbon atoms diffuse away from ferrite and enrich untransformed austenite. When the reaction proceeds under the local equilibrium between ferrite and austenite at the interface, the enrichment of carbon occurs in austenite at the vicinity of the interface[3]. As illustrated in **Fig. 4**, carbon enriched area is likely to remain untransformed. Therefore, increases in the area of the ferrite-austenite interface and the volume fraction of ferrite are effective for increasing the amount of retained austenite. The effect of the ratio between the volume fraction of ferrite and its grain size V_{PF}/d_{PF} on the product of strength and elongation (TS × T.El) can be seen in **Fig. 5**[3]. Here, V_{PF} and d_{PF} are calculated using a metallurgical model[5]. There is a correlation between the ratio V_{PF}/d_{PF} and the TS-T.El product . The higher the value V_{PF}/d_{PF}, the larger the TS-T.El product can be obtained. Low temperature hot rolling and the controlling the cooling pattern on the run out table (ROT: the cooling zone after finish rolling) are effective to increase the volume fraction of ferrite and to refine ferrite grains at

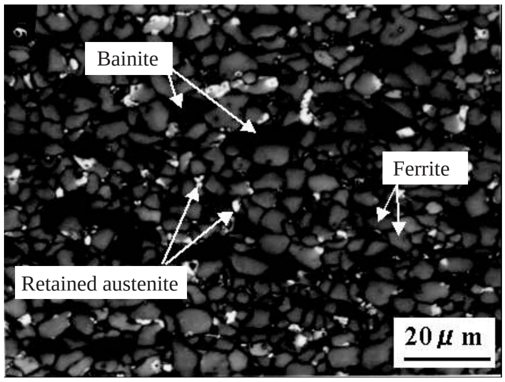

Fig . 3 A typical optical microstructure of as-hot-rolled low-alloy TRIP steel (special etching[4])

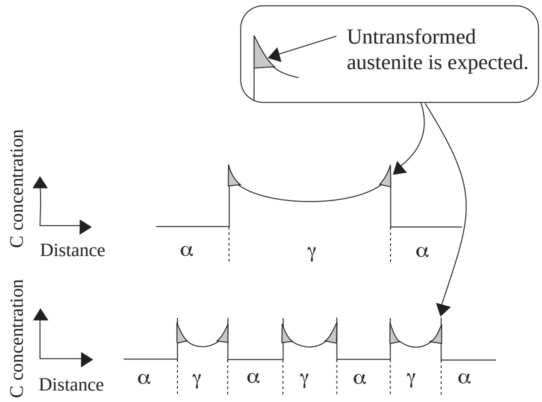

Fig . 4 Carbon concentration profiles in ferrite and austenite during the fomation of ferrrite

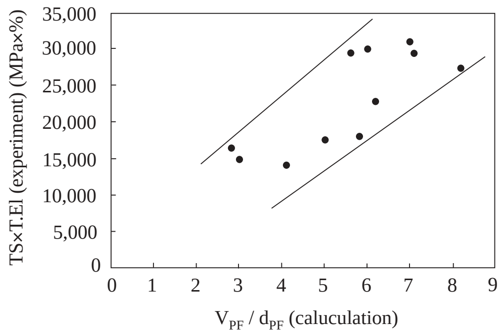

Fig . 5 Effect of the ratio between volume fraction and grain size of polygonal ferrite (V_{PE}/d_{PF}) on TS × T.El of as-hot-rolled low-alloy TRIP steels

the same time. Cooling on the ROT contains a slow cooling around the ferrite transformation nose and as a result, the transformation of ferrite is effectively accelerated.

(2) Bainite transformation: It is known from thermodynamics that ferrite transformation cannot lead to a sufficient enrichment of carbon to stabilize austenite at room temperature. Bainite transformation is, therefore, used to attain further carbon enrichment of austenite. When the formation of cementite is retarded by adding alloying element such as Si, the enrichment of carbon in untransformed austenite proceeds further as bainite transformation advances and as a result, austenite is stabilized to retain at room temperature. When the untransformed austenite is not stable enough, martensite forms during cooling. The steel sheets are coiled at around 400°C after hot rolling and cooling to stabilize austenite effectively[3].

2.2 Mill scale production of hot-rolled steel sheets containing retained austenite

The developed hot-rolled steel sheets containing retained austenite are excellent in stretch formability due to their large elongation. However, good stretch flangeability is often required in the press forming of chassis components. As it is well established, stretch flangeability is influenced significantly by the microstructure. By lowering the carbon concentration of the steels and controlling hot rolling conditions, retained austenite and bainite are dispersed in fine ferrite grains, which improved stretch flangeability without deteriorating the elongation. Stretch flangeability is evaluated by hole expanding test, and the hole expansion ratio λ between the original hole diameter *do* and the final hole diameter *d* (λ (%) = 100 × (*d* – *do*) / *do*) is used as its indicator.

The mechanical properties of the hot-rolled steel sheets containing retained austenite (elongation type and high burring type) produced on a commercial production line are shown in **Table 1** and **Fig. 6**. The elongation type steel has an elongation twice as large as that of conventional steel, while its hole expansion ratio is the same as that of the conventional steel. The burring type steel shows an elongation higher than that of conventional steel, while its hole expansion ratio is 1.4 times larger than that of the conventional steel.

In addition to the above, good weldability and high fatigue resistance are also required of a steel sheet for automobile use. Two TS780MPa class hot-rolled steel sheets containing retained austenite of 2.3 mm in thickness were spot welded to each other using CF type electrodes of 8 mm in diameter under an electrode force of 625 kgf. In **Fig. 7**, the changes of the tensile shear strength (TSS) and cross-tension strength (CTS) of the weld joints are plotted against the welding current[6]. Nuggets formed at welding currents higher than 7 kA. 4,000 kgf of TSS and 2,200 kgf of CTS are achieved at welding currents between 8.5 and 10 kA. Although CTS fluctuated above the expulsion current of 11 kA , it did not fall drastically and the strength of the weld joints was as high as that of conventional high-strength steel sheets.

High fatigue strength is also required for hot-rolled steel sheets for chassis components. DP steel is widely known to show high fatigue strength[7]. The fatigue strength of DP steel is higher than that of precipitation-hardened steel or fully bainitic steel as a consequence of cyclic hardening at the initial stage and small softening due to stable fine dislocation cell structure produced during the initial cyclic hardening. It is also known that dispersed fine martensite particle retards the propagation of fatigue cracks and the α phase strengthened by Si suppresses the initiation of fatigue cracks[7]. Here, the cyclic hardening means the increase in stress amplitude during a strain-controlled fatigue test. The same effect is observed for steels containing retained austenite. In addition to this, the deformation-induced transformation of retained austenite, which occurs at the vicinity of a stress concentrated area, can relax the stress field and introduce a compressive stress which is also considered to improve fatigue strength[8]. In **Fig. 8** the results of plane bending fatigue test

Table 1 Mechanical properties of as-hot-rolled low-alloy TRIP steels (examples of mill scale products)

	TS (MPa)	T.El (%)	λ (%)
Elongation type	810	34	45
High burring type	791	28	70

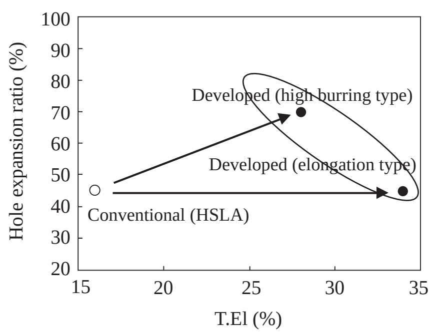

Fig . 6 Elongation-hole expansion ratio combination of developed as-hot-rolled low-alloy TRIP steels

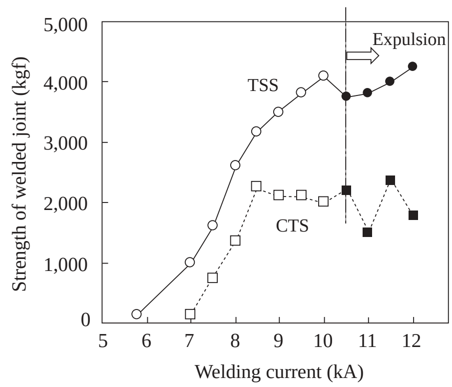

Fig . 7 Spot weldability of 780MPa grade as-hot-rolled low-alloy TRIP steels

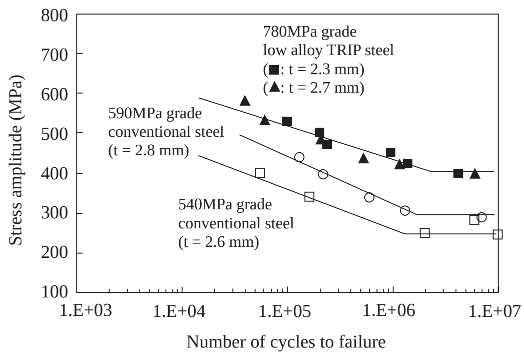

Fig . 8 Fatigue property of 780MPa grade as-hot-rolled low-alloy TRIP styeels (plane bending fatigue test)

of TS780MPa class hot-rolled steel sheets containing retained austenite of 2.3 and 2.7 mm in thickness are compared with conventional 540 and 590MPa hot-rolled steel sheets with the same level of elongation[6]. The fatigue strength of the developed high-strength steel sheets after 2×10^6 cycles was 400 MPa that is 1.4 to 1.5 times higher than that of conventional steel sheets with the same press formability.

3. 780MPa Class High Burring Hot-rolled Steel Sheets

Application of 780MPa class hot-rolled steel sheets to underbody components such as lower suspension arm is being studied. The final shape of such components requires a very high stretch flangeability as well as a large elongation. For this purpose, the development of a steel sheet satisfying the conditions El > 20% and λ > 80% at the same time is required. The method to control the microstructure through the optimization of steel chemistry and hot rolling conditions was studied and, as a result, a 780MPa class high-burring hot-rolled steel sheet with a combination of an excellent elongation and a very high stretch flangeability was developed.

3.1 Basic metallurgy for controlling microstructure of high burring hot-rolled steel sheet

Both good elongation and high stretch flangeability are indispensable for the press forming of underbody components such as a lower arm (see **Fig. 9**). In general, these properties are deteriorated with increasing the strength of steel[9, 10]. Although it is possible to enhance either of these two properties by controlling the microstructure[11], the method of controlling the microstructure to enhance both of them at the same time is not well established. Although it is suitable to enhance the elongation steels with mixed microstructures of soft ferrite (F) and hard phases such as martensite (M) etc, show poor stretch flangeability. Steels with acicular ferrite (A.F.) single phase microstructure, on the other hand, are suitable for enhancing stretch flangeability, which is governed by local ductility, but not for elongation (see **Fig. 10**). The authors then studied steel chemistry and hot rolling conditions for the purpose of finding out the optimum microstructure with which a good combination of elongation and stretch flangeability can be obtained. It was clarified from the study that the combination can be obtained when the microstructure is a mixture of ferrite and bainite in which the hardness difference between the two phases is minimized by solution hardening to make the microstructure as uniform as possible. The following conditions are adopted to maintain the microstructure. (i) In order to enhance the formation of ferrite and to control the shape of ferrite, the amount of austenite former elements such as carbon and manganese are reduced, and a two-step cooling at the ROT is adopted. In addition, (ii) the formation of an undesirable hard phase is suppressed by reducing the carbon content.

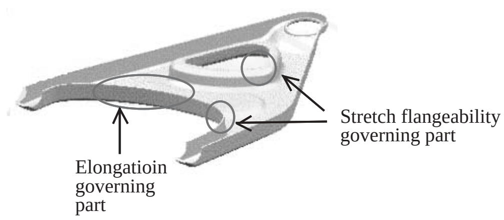

Fig. 9 Appearance and required forming properties of a lower arm

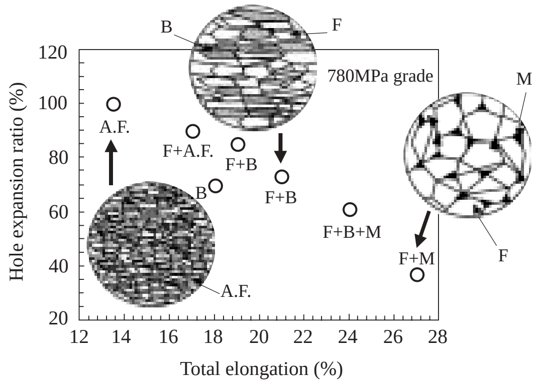

Fig. 10 Relatioin between total elongation and hole expansion ratio of 780MPa as-hot-rolled steels, and their microstructural feature

3.2 Mill trial of high-burring hot-rolled steel sheet

On the basis of the above metallurgical concept, a mill trial of the high-burring- hot-rolled steel sheet was conducted. **Table 2** shows the mechanical properties of the developed product in comparison with those of a conventional product. As a result of the reduced contents of C and Mn, the A_{r3} transformation temperature[12] of the developed steel sheet is raised by 53°C, and thus the formation of ferrite is accelerated. The reduced content of Mn has proved effective, at the same time, for inhibiting the segregation of Mn during casting and as a consequence, enhancing the uniformity of microstructure. As a result, a good combination of elongation and stretch flangeability were obtained, meeting the target, El > 20% and λ > 80%, as seen in **Fig. 11**. An example of the microstructure of the developed steel is compared with conventional steel in **Fig. 12**. It can be seen in the pictures that the microstructure of the developed steel is a mixture of ferrite and bainite, and that the volume fraction of ferrite is higher and more polygonal than the conventional steel.

Fatigue property of the developed steel was compared with a 590

Table 2 Comparison of mechanical properties between developed and conventional 780MPa grade high burring steels

	A_{r3} (°C)	ROT 2 steps	TS (MPa)	El (%)	λ (%)
Developed	789	Yes	797	22	84
Conventional	736	No	795	19	74

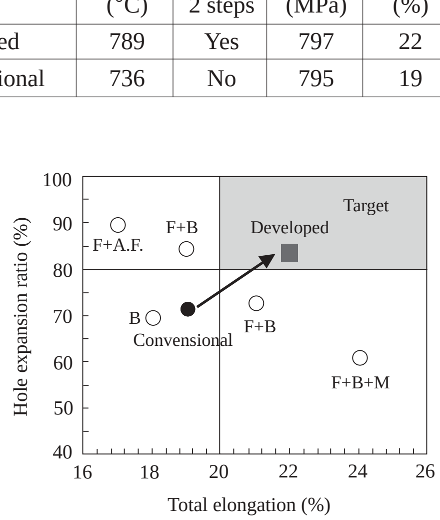

Fig. 11 Combination between total elongation and hole expansion ratio of developed 780MPa steel

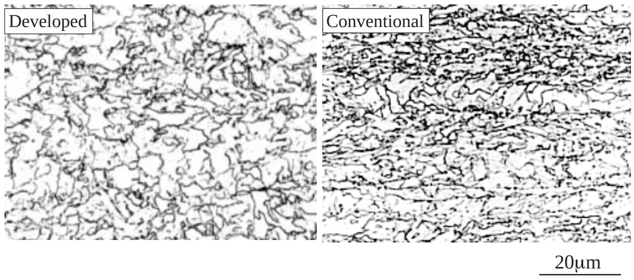

Fig. 12 Microstructures of developed and conventional 780MPa grade steels

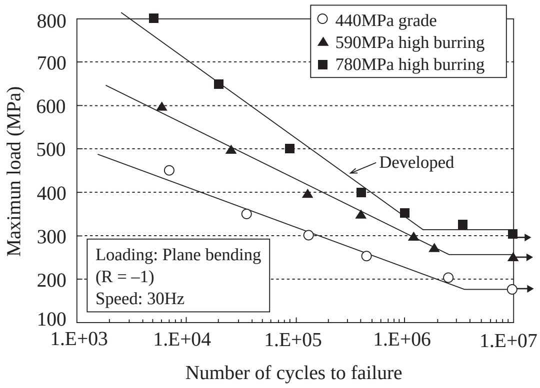

Fig. 13 Fatigue property of developed 780MPa grade high burring steel (plane bending fatigue test)

Table 3 Fatigue limit ratio of developed steel

Steel	440MPa (conventional)	590MPa High burring (conventional)	780MPa High burring (developed)
Fatigue limit ratio	0.38	0.42	0.40

Fatigue limit ratio = (fatigue strength at 10^7 cycles)/TS

MPa class high-burring steel sheet and a 440MPa class conventional steel in **Fig. 13**. With respect to fatigue limit ratio, which is defined as the ratio between the fatigue strength of a steel sheet after 10^7 cycles and its tensile strength, it is clear that the developed steel sheet does not show any significant deterioration of the fatigue limit ratio in spite of its high strength from the result of a plane bending fatigue test under a stress ratio of –1 as shown in **Table 3**. In the developed steel, the strengthening is fully reflected in the fatigue properties.

4. Conclusions

The weight reduction of underbody components is expected to have a considerable contribution in the weight reduction of an auto-body in the near future. Development of hot-rolled steel sheets with excellent press formability and fatigue strength are indispensable. The hot-rolled steel sheets with retained austenite and the high-burring hot-rolled steel sheet presented in this paper are expected to contribute significantly to the weight reduction of an auto-body when they are applied widely to its components.

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