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Highly Formable Sheet Steels for Automobile through Advanced Microstructure Control Technology*

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Synopsis:

In the process of developing steel sheets for automobiles, Kawasaki Steel has been aiming at better formability of high strength steel sheets and the improvement of other various properties. Typical examples of the development includes, a new bake hardenable steel (BHT steel) sheet having characteristics in that not only yield strength but also tensile strength are increased by baking after coating, and Super HSLA steel sheet having excellent elongation and hole expansion property, both at a high level of performance through the refining of crystal grains brought about by dynamic recrystallization. Both steel sheets have been secured as the results of the sophisticated control of steel structure, performed at the application of completely new metallurgical findings, combined, as their basis, with new technology devised at the No. 3 hot strip mill in Chiba Works which initiated its operation in 1995.

1 Introduction

Increasing concerns over global environmental problems and consumers' demand for higher collision safety of motor vehicles impose conflicting requirements on auto bodies: they are required to be both lighter and stronger. In addition, ongoing technological innovations such as the commercialization of fuel-cell vehicles could revolutionize the concept of motor vehicles and functions required of them, as well as the materials used for auto bodies. Various new lightweight materials such as aluminum, magnesium, and plastics have been proposed, and these materials are already used commercially in specific types of vehicles and components. However, these materials still have problems such as formability, reliability, and recyclability as well as cost, and hence the scope and volume of their application remain limited. Expectations are therefore increasing for ferrous materials, which account for the major proportion of materials of a motor vehicle and could make vehicles lighter while improving collision safety.

Typical characteristics required of ferrous materials used for auto bodies are excellent press formability and weldability during assembling, corrosion resistance as a completed vehicle, fatigue resistance and other strengths as components, and crashworthiness when involved in a collision. Although these characteristics are required of the steel sheets themselves, many of the characteristics also need to be evaluated for the assembled auto body as a whole. Thecnological development on effectively using ferrous materials is thus also important. Ferrous materials are generally considered to be general-purpose materials, but the required characteristics actually depend on the positions where they are used, and ferrous materials of different thickness, strength, and formability are used with or without galvanizing. Accordingly, almost no identical materials are used at different positions.

High strength steel sheets play a crucial role in making vehicles lighter while securing collision safety. High strength steel sheets with various strengths, improved formability, weldability, and fatigue resistance are increasingly being used commercially. Generally, steel-strengthening methods include solution strengthening, grain refinement strengthening, transformation strengthening, precipitation strengthening, and strain age strengthening, which are used alone or in combination, while adding appropriate alloying elements and applying thermo-mechanical treatment. In many cases, however, steel strengthening tends to degrade other properties, and so a strengthening method that also improves other properties needs to be developed.

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Kawasaki Steel has tried to enhance the accuracy of microstructure control for developing various types of automotive ferrous materials having markedly improved properties, as well as to develop technologies for effectively using ferrous materials.

This paper outlines two examples of newly commercialized automotive steel sheets. The first is a new high strength hot rolled steel sheet that has excellent strain age hardenability, the tensile strength of which is increased by paint baking treatment (BHT steel sheet). The second is a highly formable high strength hot rolled steel sheet obtained by applying dynamic recrystallization to refining crystal grains (Super HSLA steel sheet). These new types of steel sheets not only have unique microstructures that exhibit excellent properties, but the methods and matallurgical principles used to create such structures are also new.

2 High Strength Hot Rolled Steel Sheet with Excellent Strain Age Hardenability (BHT Steel Sheet)

2.1 Features of BHT Steel Sheet and Its Metallurgical Principle

A new high strength hot rolled steel sheet that has excellent strain age hardenability was successfully developed.[1,2] This steel sheet has low strength while being formed, and thus exhibits excellent formability, but its tensile strength is markedly increased by paint baking treatment. It also has good aging resistance at room temperature. **Figure 1** schematically shows the stress-strain relationship of the newly developed steel sheet after strain aging treatment. The new steel sheet is characterized by the fact that both its yield strength and tensile strength are significantly increased by strain aging treatment, which is a key difference from conventional BH steel sheet. This property is effective for increasing energy absorption in a vehicle collision, and so the new steel sheet is expected to be widely used for structural members of vehicles.

The excellent strain age hardenability of this steel sheet is achieved by using the function of N, which has higher solubility than C in the hot rolling temperature range. In order to secure the solubility of N in the steel sheet, the cooling condition after hot rolling is controlled to suppress the precipitation of AlN. Further, in order to suppress the property deterioration on room temperature aging caused by the diffusion of N, the steel sheet is quickly cooled to refine the grain size and enlarge the area of grain boundaries. As the grain boundaries are stable positions for solute N, precipitation of N in the grain boundaries is promoted. Thus, excellent strain age hardenability and aging resistance at room temperature are simultaneously obtained. This steel sheet is being steadily produced at the Chiba Works' new hot strip mill, utilizing the highly accurate cooling technology developed there.

2.2 Strain Age Hardenability of the New Steel Sheet and Mechanism of Tensile Strength Increase

The newly developed steel sheet was given prestrain in the range of 0 to 15%, and subjected to baking at 170°C for 20 min in an oil bath. The effect of prestrain on the amounts of BH and BHT of the newly developed steel sheet was compared with that of a conventional steel sheet. The result is shown in **Fig. 2**. The amounts of BH and BHT are the increases of yield strength and tensile strength respectively by paint baking treatment. Their definitions were as shown in Fig. 1.

Both the amount of BH and amount of BHT were low in the conventional steel sheet, and strength increase by paint baking treatment was negligibly small. In contrast, the new steel sheet that was given prestrain of 2% exhibited the amount of BH of almost 100 MPa, while the amount of BHT, which corresponds to tensile strength, was also markedly increased. The amount of BHT increased with increasing prestrain, reaching around 60 MPa when prestrain of 10% was given. The amount of BHT did not change much when the prestrain was

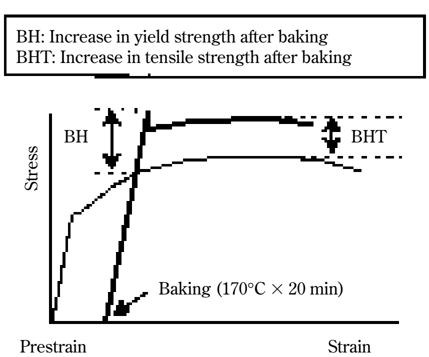


Fig. 1 Stress-strain relationship of newly developed steel after strain aging

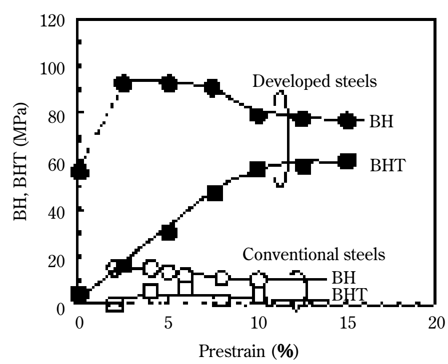
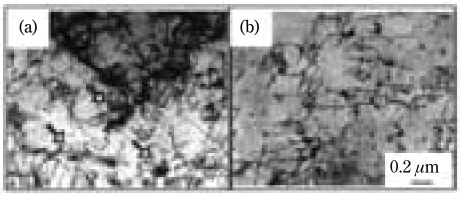


Fig. 2 Effect of prestrain on BH and BHT of newly developed steels after strain aging (t = 1.4 mm)



(a) 10% prestrain → 170°C × 20 min → 4.5% strain
(b) 14.5% strain

Photo 1 Dislocation networks of developed steel induced by tensile strain with or without baking treatment

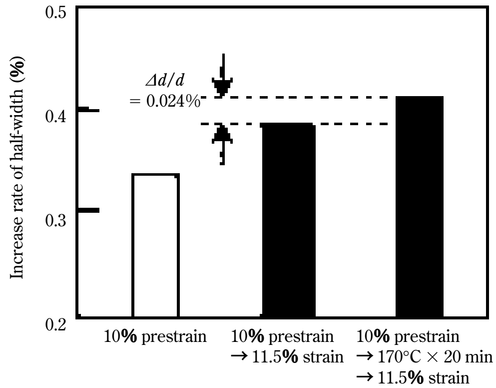


Fig. 3 Effect of baking treatment on (222) peak half-width of developed steel

increased beyond 10%.

The mechanism of tensile strength increase by paint baking treatment of the new steel sheet was investigated. **Photo 1** shows the effect of paint baking treatment on the TEM microstructure of the new steel sheet that was subjected to tensile testing. Photo 1 (a) is the result of TEM observation of the steel sheet that was first given 10% prestrain, then subjected to paint baking treatment, and then given a further 4.5% strain. Photo 1 (b) shows the case where 14.5% strain was given without paint baking treatment. Dislocation loops and tangles are clearly observable in the material subjected to paint baking treatment, indicating the increased dislocation density. In contrast, the dislocation density is low in the material not subjected to paint baking treatment even though the same amount of deformation was given. This is considered attributable to the fact that the dislocation introduced by the prestrain was firmly anchored by solute atoms when the material was subjected to paint baking treatment, and the multiplication of dislocation was promoted by the plastic deformation given after paint baking treatment. The external force required for the multiplication of dislocation is proportional to how firmly the dislocation is anchored to the dislocation source. The external force required for the dislocation to move in the region where the multiplication of dislocation progressed is proportional to the dislocation density. It is considered that the tensile strength is increased because the stress required for causing plastic deformation is increased due to these phenomena.

In order to confirm these phenomena, the change in the dislocation density by paint baking treatment was examined by the X-ray diffraction half-width. The (222) peak half-width (d) was measured for two types of materials, one subjected to paint baking treatment, the other without paint baking treatment, and the rate of increase of the half-width ($\Delta d/d$) was evaluated. **Figure 3** compares the results obtained for two types of materials. One material was first given 10% prestrain, then subjected to paint baking treatment, and then given a further 11.5% strain. The other was given the same 21.5% strain without paint baking treatment. As the figure shows, paint baking treatment increased the X-ray diffraction half-width, and hence it was confirmed that paint baking treatment increases the dislocation density.

Thus, the strength of the newly developed steel sheet is markedly and stably increased by subjecting it to paint baking treatment after press forming.

2.3 Properties of the New Steel Sheet and Its Applications

Table 1 compared typical mechanical properties of the newly developed steel sheet of TS 440 MPa class manufactured by the actual line with those of a conventional hot rolled steel sheet of the same class. The newly developed steel sheet exhibits mechanical properties equivalent to the conventional steel sheet, while having excellent strain age hardenability. It was also confirmed that the newly developed steel sheet has equivalent properties in press formability such as forming limit and spring back.

In order to evaluate crashworthiness as an automotive steel sheet, a high strain rate tensile test was carried out on the new and conventional steel sheets applying the strain rate of 2 000 s^{-1} and their dynamic deformation behavior was observed. The materials were tested both in the as-produced condition, and after giving 10% prestrain and subjecting them to paint baking treatment. The absorbed energy was calculated by integrating the value of stress up to the strain of 15%.

Figure 4 shows the effect of paint baking treatment on absorbed energy at high strain rate. The absorbed energy of as-produced materials increases with increas-

Table 1 Typical mechanical properties of developed steel (t = 1.4 mm)

	YS (MPa)	TS (MPa)	El (%)	BH* (MPa)	BHT** (MPa)
Developed steel	370	478	34	95	57
Conventional steel	347	480	34	14	9

*Increase in yield strength by aging at 170°C for 20 min after 2% prestrain
**Increase in tensile strength by aging at 170°C for 20 min after 10% prestrain

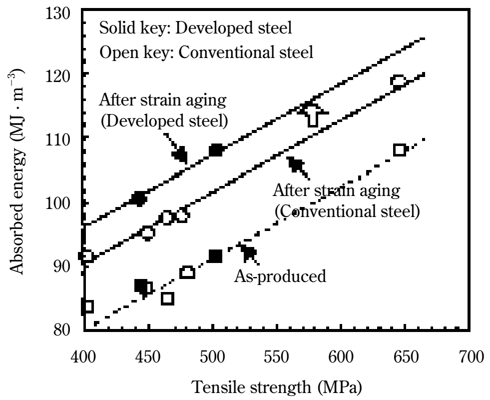


Fig. 4 Absorbed energy at high strain rate tensile tests of newly developed steel and conventional steel

ing tensile strength of the materials. The new and conventional steel sheets show identical correlation between the absorbed energy and tensile strength when tested in the as-produced condition. When they were tested after giving 10% prestrain and paint baking treatment, the absorbed energy showed a positive correlation with the tensile strength of each material. However, the absolute value of absorbed energy for the newly developed steel sheet is higher than that for the conventional steel sheet. The absorbed energy is increased by work hardening for both the conventional steel sheet and the newly developed steel sheet, but for the latter there is also the contribution of tensile strength increase due to strain age hardening. The contribution of strain age hardening is equivalent to the tensile strength increase of about 60 MPa in as-produced materials. The tensile strength increase (BHT) observable in normal tensile tests appears also in high strain rate tensile tests.

Based on the data obtained in this test, FEM analysis was carried out to evaluate the effect of the newly developed steel sheet on improving crashworthiness when used as a structural member of a vehicle. It was found that the contribution from the strain age hardening corresponds to a half-gauge (0.1 mm) increase in the sheet thickness and to a 60 to 70 MPa increase in tensile strength. Thus, it was confirmed that the newly developed steel sheet can make a vehicle significantly lighter as thinner gauge sheets can be used. It also helps make a vehicle lighter thanks to its excellent formability for various parts of complex shapes that are difficult to form, thus reducing the strength of sheet required for such parts.[3)]

Conventional steel sheets that have strain age hardenability suffer deterioration of mechanical properties while held at room temperature. In contrast, the newly developed steel sheet held at room temperature for one year showed only negligible changes in properties: the tensile strength showed almost no change, the yield strength increased by about 30 MPa, and the elongation lowered only by 1%.

The newly developed steel sheet is produced by controlling the chemical composition and grain size of steel and is characterized by excellent strain age hardenability and less deterioration of properties by room temperature aging.

The newly developed steel sheet allows crashworthiness to be improved without increasing vehicle weight, or conversely a vehicle to be made lighter while maintaining crashworthiness, and is expected to make a significant contribution to safety and environmental issues associated with motor vehicles. It was already reported that the use of this steel sheet for anti-collision members reduced the weight of a mass-produced vehicle by more than 10%.[4)] This steel sheet is expected to be widely used in motor vehicles in the future.

3 Highly Formable High Strength Hot Rolled Steel Sheet Obtained by Applying Dynamic Recrystallization for Refining Crystal Grains (Super HSLA Steel Sheet)

3.1 Metallurgical Principle

High strength hot rolled steel sheets are widely used in undercarriage parts of motor vehicles. These parts are generally produced by punching holes and forming flanges around them: so-called hole expansion. Therefore, the material sheets require excellent elongation and hole expansion properties. Hole expansion is known to be improved by refining the grain size of the steel sheet. Various studies are now underway in Japan and overseas countries on how to refine the grain size.

Dynamic recrystallization is used as a grain refining method in the hot rolling process for producing the newly developed Super HSLA steel sheet.[5,6)] In dynamic recrystallization, crystal grains that have a low dislocation density are formed and grow during processing that gives a high-temperature deformation.[7)] Crystal grains formed by dynamic recrystallization are generally fine in size and polygonal. In particular, crystal grains obtained in the low-temperature, high-strain-rate region can remain stable without growing for a comparatively long time. However, dynamic recrystallization generally occurs only in the rough rolling region that has a low Z (Zener-Holloman) parameter, which is commonly used to describe high-temperature deformation and is given by Eq. (1).

$$Z = \dot{\varepsilon} \exp (Q/RT) \cdots\cdots (1)$$

In order to cause dynamic recrystallization in the high-Z region such as finish rolling, the initial austenite grain size needs to be sufficiently small. In this new steel sheet, TiC was used to suppress the grain growth during slab reheating. Nb forms NbC and has the same effect. However, it was experimentally shown that Ti does not greatly hinder recrystallization, whether dynamic or sta-

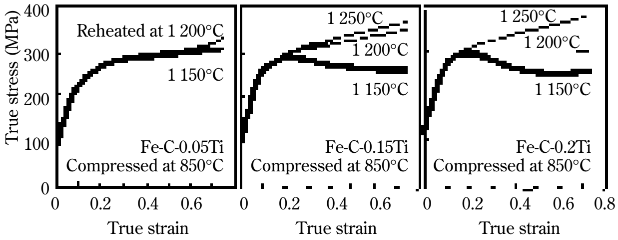


Fig. 5 True stress-true strain curves of steels with different reheating temperatures and Ti contents (in mass%)

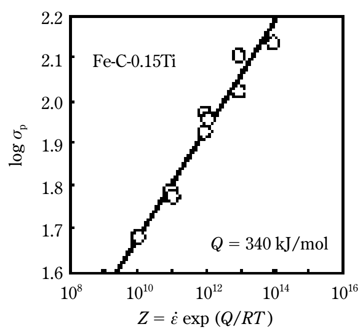


Fig. 6 Relation between peak stress and Z parameter in Ti-added low carbon steels

tic. In other words, Ti does not cause much grain elongation, which deteriorates hole expansion, even if the rolling temperature moves from the dynamic recrystallization region to the static recrystallization region near the final pass of hot rolling.

Steels having different Ti contents were experimentally prepared, reheated to different temperatures, and compressed at 850°C, a temperature corresponding to the finish rolling temperature zone in hot rolling. The relation between true stress and true strain was examined in each case (**Fig. 5**). When a material undergoes dynamic recrystallization, its true stress-true strain curve exhibits a particular shape that has a peak. The stress increases with increasing strain until the strain reaches a certain strain level (ε_p), where it shows the peak stress (σ_p), then begins decreasing and becomes constant after the strain passes a certain value. These curves show that dynamic recrystallization tends to take place when the Ti content is high, and the reheating temperature is low. This is because the amount of TiC precipitation increases with decreasing compression temperature, and accordingly the γ grain size becomes smaller. In the case of low-carbon steel as in this test, dynamic recrystallization takes place even in the finish rolling region when the austenite grain size is less than about 50 μm.

The values of the peak stress obtained by the compression test were plotted against the values of the Z parameter (**Fig. 6**), and used to calculate the apparent activation energy. The value obtained was 340 kJ/mol,

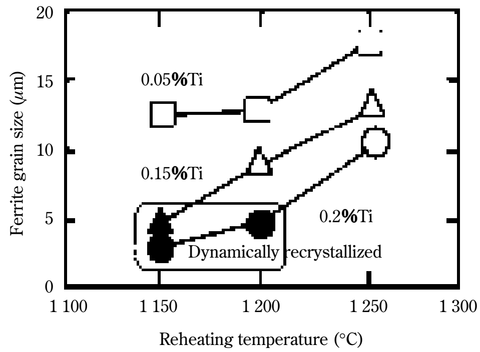


Fig. 7 Effect of heating temperature and Ti content on final ferrite grain size

which is near the self-diffusion activation energy of iron (285 kJ/mol). Thus, dynamic recrystallization that takes place in these materials is interpreted with good consistency in terms of activation energy as well.

The ferrite grain sizes in the materials experimentally compressed to the true strain of 0.7 and cooled at a rate of 50°C/s were plotted as a function of reheating temperature (**Fig. 7**). The ferrite grain sizes in the materials in which dynamic recrystallization took place (shown by solid keys in the figure) are markedly smaller than those in the materials in which static recrystallization took place. Thus, it was confirmed that a microstructure with very fine and uniform grain sizes of less than 5 μm was obtained by dynamic recrystallization.

3.2 Material Properties of the New Steel Sheet

Currently, the Super HSLA steel sheets of 590 MPa class and 780 MPa class are being produced at Chiba Works. In both classes of steel sheets, it was confirmed that the flaw stress is reduced by 10 to 20% during finish rolling, and that dynamic recrystallization can be achieved in a commercial hot rolling process. **Photo 2** shows the microstructures of the newly developed Super HSLA steel sheet and conventional HSLA steel sheet. The average ferrite grain size in the conventional steel sheet is 6 to 7 μm, while that in the Super HSLA steel sheet is as fine as about 2 μm. Thus, the company was the first in the world to successfully produce, on an industrial scale, steel sheets that have ultra-fine grains.

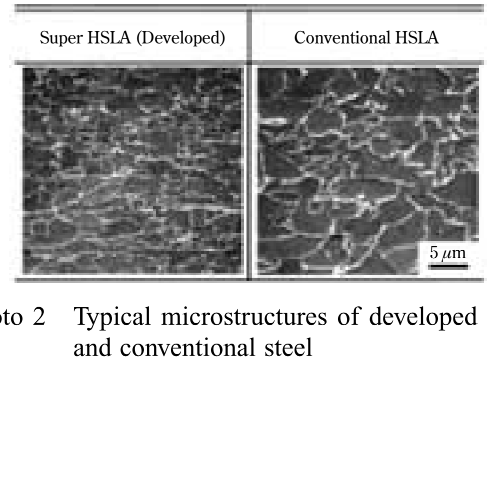


Photo 2 Typical microstructures of developed steel and conventional steel

Table 2 Mechanical properties of developed steel

Grade	Steel type	YS (MPa)	TS (MPa)	El (%)	λ* (%)	FL** (MPa)
590 MPa	Super HSLA	480	600	31	120	280
	Conventional HSLA	510	600	27	60	250
780 MPa	Super HSLA	690	790	22	80	370
	Conventional HSLA	710	790	20	40	310

*λ: Hole expansion ratio
**FL: Fatigue limit in bending mode

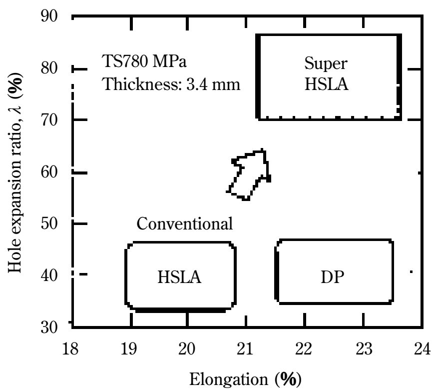


Fig. 8 Elongation and hole expansion ratio of developed steel

The EBSD (electron back scattering diffraction) analysis of the microstructure of the newly developed steel sheet confirmed that the boundaries of adjacent grains have high angles of more than 15°. **Table 2** shows the mechanical properties of the newly developed steels of 590 MPa class and 780 MPa class. **Figure 8** compares the elongation and hole expansion ratio of the newly developed steel sheet of 780 MPa class those of the conventional HSLA steel sheet. Both elongation and hole expansion ratio are improved, whereas generally in the past, it was difficult to improve these two properties simultaneously. The formability of the new hot rolled steel sheet was markedly improved due to excellence in both of these two conflicting properties. The new steel sheet also has superior fatigue strength, weldability and corrosion resistance to the conventional HSLA, and is expected to be widely used for producing undercarriage parts such as transverse links and loads wheels.

4 Conclusions

New automotive steel sheets were developed for making vehicles lighter while securing collision safety. The BHT steel sheet is a completely new type of steel sheet that has low strength and therefore excellent formability while being formed, but its tensile strength is markedly increased by paint baking treatment. Its application to auto bodies effectively improves absorbed energy at collision, which is becoming a major issue related to vehicle safety. The Super HSLA steel sheet was fabricated by incorporating dynamic recrystallization in the hot rolling process of steel sheets for the first time in the world, thus dramatically improving the hole expansion property of the hot rolled steel sheet used for producing undercarriage parts.

The bodies of some of the recently released automobiles contain more than 50% high tensile strength steel. This percentage will increase in the future as the strength of the steel sheet itself is increased. The two types of steel sheets introduced here fully meet the increasing needs for even higher strength steel sheets.

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