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High Strength Steel Sheets for Automobile Suspension and Chassis Use —High Strength Hot-Rolled Steel Sheets with Excellent Press Formability and Durability for Critical Safety Parts—†

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Abstract:

JFE Steel has developed two new high strength hot-rolled steel sheets which provide excellent performance in automobile suspension and chassis parts: (1) "NANO-HITEN," a new precipitation-hardened high strength hot-rolled steel sheet in which precipitates are refined to a size of several nanometers, giving the material an excellent balance of elongation and the hole-expansion ratio, and (2) "BHT steel sheet (bake-hardenable steel with tensile strength increase)," a new strain-aging type high strength hot-rolled steel sheet which features low strength and high formability during forming and a large increase in tensile strength after paint baking, resulting in a higher fatigue limit and improved crash-worthiness. This paper describes the features and properties of these new products.

1. Introduction

As a measure to reduce energy consumption, reduction of vehicle weight is very important as well as improvement of efficiency adoption of a new system in the power train.[1)] Consequently, reduction of body weight, which accounts for approximately 25% of total vehicle weight, has become an important technical issue.[2–4)]

On the other hand, with strengthening of automobile collision safety regulations and the start of public disclosure of crash test results, automakers are developing bodies with excellent crashworthiness. However, the weight of these bodies tends to increase due to the increase in sheet thickness, the increase in numbers of reinforcement.[5)]

Against this social background, the two mutually contradictory functions of lighter weight and greater strength are required in automobile bodies in order to reduce vehicle weight and improve crashworthiness. Expanded application of high strength steel sheets is extremely important for reducing auto body weight and securing crashworthiness.

The suspension and the chassis are positioned as critical safety parts, and therefore high reliability is required in addition to their basic functions as parts. Application of high strength steel sheets to these parts not only has a simple body weight reduction effect, but also has the effect of improving riding comfort and driving stability. In actual applications, high strength steel sheets must provide a diverse range of functions, including not only high press-formability, which is necessary for manufacturing complex part shapes, but also weldability during assembly, corrosion resistance and fatigue resistance properties in the finished automobile, and impact resis-

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tance in collisions.

This paper introduces two new high strength hot-rolled steel sheets developed by JFE Steel for use in automotive suspension and chassis parts: (1) "NANOHITEN," a new precipitation-hardened high strength hot-rolled steel sheet in which precipitates are refined to the size of several nanometers, giving the material both high elongation and a high hole-expansion ratio, and (2) "BHT steel sheet," a new strain-aging type high strength hot-rolled steel sheet which makes it possible to increase tensile strength substantially by paint baking.

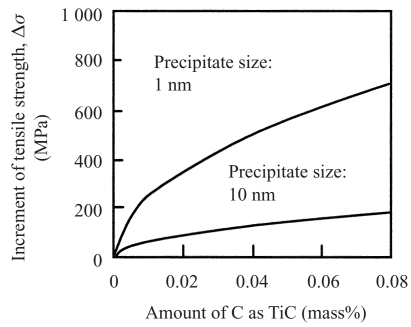

Fig. 2 Effects of size and amount of precipitates on the increment of tensile strength

2. New Precipitation Hardened High Strength Hot-Rolled Steel Sheet, "NANOHITEN"

2.1 Principle and Features of NANOHITEN

Because complex deformation modes including stretch-forming, burring and other types of stretch-flange forming are frequently used in press-forming underbody parts such as the suspension and chassis, a sufficient balance of elongation and the hole-expansion ratio is required in high strength hot-rolled steel sheets. To realize these properties, JFE Steel began development of a TS780 MPa grade high strength hot-rolled steel sheet based on a new metallurgical concept, and succeeded in developing and commercializing a new sheet with unique properties, NANOHITEN (NANO: new application of nano obstacles for dislocation movement).[6)]

NANOHITEN has the following three features:

(1) Single-phase ferrite structure with high formability
(2) Hardening by precipitates refined to the size of several nanometers
(3) Extremely high thermal stability of precipitates

Figure 1 shows the effect of the microstructure on the elongation-hole expansion ratio balance (El-λ). With multi-phase structures, as represented by dual-phase (DP) steels, high elongation is accompanied by the disadvantage of a low hole-expansion ratio. Conversely, with single-phase structures such as single-phase bainite steel, the hole-expansion ratio is high, but elongation is low. Therefore, in the development of NANOHITEN, the authors noted the high elongation of ferrite and high-hole expansion ratio of single-phase structures, and attempted to improve the hole-expansion ratio while maintaining high elongation by adopting a single-phase ferrite structure. However, with conventional techniques, it is not easy to achieve strength of the TS780 MPa level and higher in single-phase ferritic steels.

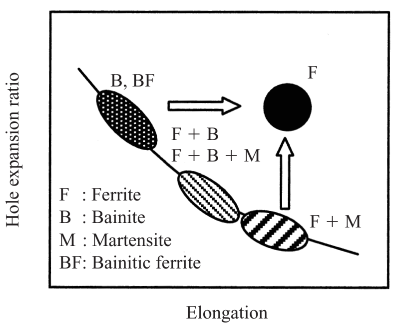

Fig. 1 Effect of microstructure on elongation-hole expansion ratio balance

Figure 2 shows a calculation of the relationship between the amount of precipitates and the increment of precipitation hardening for a precipitate size of 10 nm, which is found in conventional precipitation-hardened steels, and 1 nm, assuming the Orowan-Ashby model.[7)] Because the increment of tensile strength is determined by the distance between precipitates, the effect of precipitate size becomes more pronounced as the higher amount of precipitate. For example, when the amount of C precipitates in the form of TiC is 0.08 mass%, precipitation hardening ($\Delta\sigma$) to 700 MPa is possible with precipitates of 1 mm diameter. Based on this result, the aim in NANOHITEN was to maximize the use of precipitation hardening by refining the precipitates to a size of several nano meters. However, if refined precipitates are thermally unstable, they will be prone to coarsening due to deviations in manufacturing conditions, inviting strength reducing and deviations. Thus, thermal stability is also required in the precipitates.

Therefore, in NANOHITEN, the authors applied innovative techniques in refining the precipitates to several nano meters and improving their thermal stability. Concretely, the X-Y-C ternary carbide system was studied with various combinations of X and Y, revealing that extremely fine precipitates can be obtained in a system where proper amounts of Ti and Mo are added to a 0.04C-1.3Mn base steel composition, and these precipitates show extremely high thermal stability.[8)]

Photo 1 shows a SEM image of the microstructure of NANOHITEN and a TEM image of the precipitates (dark-field image). The microstructure is a single phase of ferrite, and a large number of ultra-fine precipitates

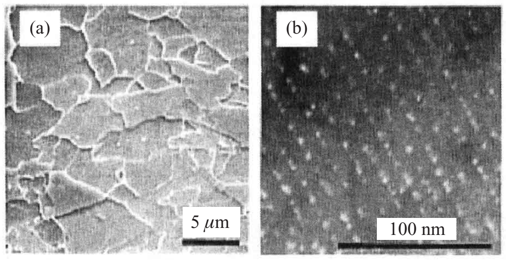

Photo 1 Microstructure(a) and precipitates(b) of NANO-HITEN

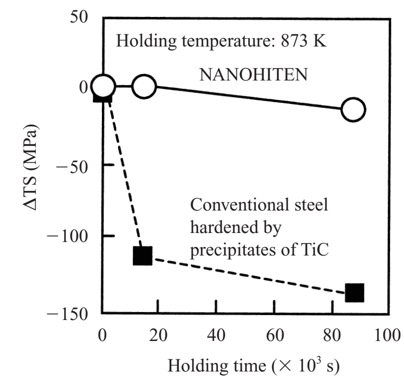

Fig. 3 Comparison in thermal stability of strength between NANOHITEN and conventional HSLA steel

with a size of approximately 3 nm have precipitated in rows. EDX (energy dispersive X-ray spectrometer) and ICP (inductively coupled plasma atomic emission spectrometer) analysis identified these precipitates as (Ti, Mo) C.

Figure 3 shows the results of a measurement of the reduction in tensile strength (ΔTS) at room temperature after sheets were isothermal kept at 650°C for a long time. When conventional sheets using TiC precipitation hardening were held for 15×10^3 s, a large drop in tensile strength associated with coarsening of TiC was observed. In contrast, NANOHITEN showed virtually no decrease in tensile strength, even when held for 80×10^3 s. This result confirms that the precipitates in NANOHITEN have extremely high thermal stability.

The hot-rolling process for manufacturing NANOHITEN does not differ in any way from the ordinary process used to manufacture general steels, and a precipitation-hardened single-phase ferrite structure can be obtained easily at a coiling temperature of 600°C or higher. The pearlite transformation frequently occurs when conventional precipitation-hardened steels are coiled at high temperature, but with NANOHITEN, a single-phase ferrite structure can be obtained consistently because the C content is held to a low level and Mo is added, preventing the pearlite from generating. In addition, unlike DP steel sheets and conventional precipitation-hardened steel sheets, which are prone to strength fluctuations, depending on coiling conditions, deviations in the tensile strength of NANOHITEN are extremely slight due to its combination of a ferrite single phase and thermally stable precipitates. This means that deviations in the amount of springback during press-forming are minimal.

As a further advantage, because precipitation occurs at coiling temperature, the rolling load with TS780 MPa grade NANOHITEN is smaller than that of the conventional TS540–590 MPa grade steel. Products with thinner sheet thicknesses and wider widths than those with the conventional TS780 MPa grade steel can be manufactured.

2.2 Properties and Applications of NANOHITEN

Figure 4 shows the results of a comparison of the El-λ balance of NANOHITEN, a conventional precipitation-hardened steel sheet, and a high stretch-flange forming (high burring) type high strength hot-rolled steel sheet. In comparison with these conventional steels, NANOHITEN shows an extremely good El-λ balance. This is attributed to the fact that NANOHITEN consists of the single-phase ferrite and ultra fine precipitates.

Figure 5 shows the relationship between the TS of the base metal and fatigue limit in a plane bending fatigue test for the respective hot-rolled sheets. In general, the fatigue limit increases as the strength of the

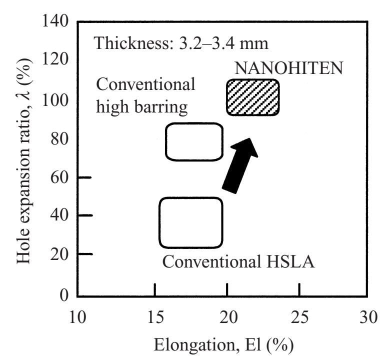

Fig. 4 Comparison of El-λ balance in 780 MPa grade hot-rolled steels

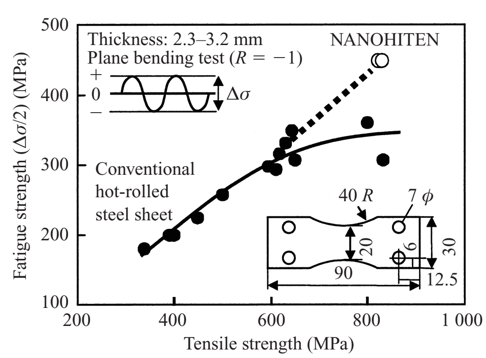

Fig. 5 Comparison of fatigue strength between NANO-HITEN and conventional HSLA steel

base material increases. However, when the strength level exceeds 590 MPa, conventional hot-rolled sheets show a smaller increase in the fatigue limit relative to the increase in the strength of the base material. In contrast, fatigue strength corresponding to the strength of the base material can be obtained in NANOHITEN. This is attributed to the satisfactory surface roughness obtained in NANOHITEN by reducing the amount of Si addition.

TS780 MPa grade NANOHITEN is being increasingly adopted, particularly in chassis and arm parts, based on the outstanding features described above. At present, it is in mass production at a level of several 100 tons per month, and expansion in its range of applications is expected in the future. Although this report has focused on the TS780 MPa grade, the NANOHITEN product line also includes TS590 and 980 MPa grades and galvannealed sheets, which can be selected to meet the property requirements of the product.

3. New Strain-Aging Type High Strength Hot-Rolled Sheet, "BHT Steel Sheet"

3.1 Principle and Features of BHT Steel Sheet

JFE Steel developed a hot-rolled steel sheet, BHT (bake hardenable steel with tensile strength increase) steel sheet which possesses low strength and high formability during press-forming and displays a large increase in tensile strength after paint baking, while also possessing a satisfactory room temperature anti-aging property, by properly adjusting the content of solute N in the steel and refining the grain size using high-accuracy cooling control after hot rolling.[9–14] BHT steel sheet has absolutely the same press-formability as conventional steel sheets, and in products, performance suitable for application as a high tensile steel, with high strength exceeding that of conventional sheets, can be obtained easily.

Table 1 shows the typical chemical composition of TS440 MPa grade BHT steel sheet. **Table 2** shows an example of the mechanical properties of the same steel in comparison with a conventional TS440 MPa grade hot-rolled steel sheet.

BHT steel sheet realizes a high strain age hardening capacity by using N, which has higher solubility in the hot-rolling temperature region than C. Therefore, precipitation of AlN is suppressed by controlling the cooling conditions after hot rolling to obtain solid solution N in the sheet. At the same time, in order to prevent room temperature aging deterioration due to diffusion of N, the area of grain boundaries is increased by performing rapid cooling immediately after hot rolling to refine the grain size, causing the solute N to segregate to the stable position at the grain boundaries.

Table 1 Typical chemical composition of TS 440 MPa grade BHT steel (mass%)

C	Si	Mn	P	S	Al	N
0.08	0.10	1.25	0.016	0.003	0.017	0.006 8

Table 2 Typical mechanical properties of TS 440 MPa grade BHT steel (Thickness: 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

Figure 6 shows the stress-strain curves of BHT steel sheet as-received and after strain aging. As the most important feature of the developed steel, unlike conventional BH steel sheets, BHT steel sheet shows a remarkable increase in yield strength when strain age hardening is performed, while tensile strength is also improved.

Figure 7 shows the effect of prestrain on BH (increase in yield strength) and BHT (increase in tensile strength) when paint baking was performed at 170ºC × 20 min in an oil bath after applying 0–15%

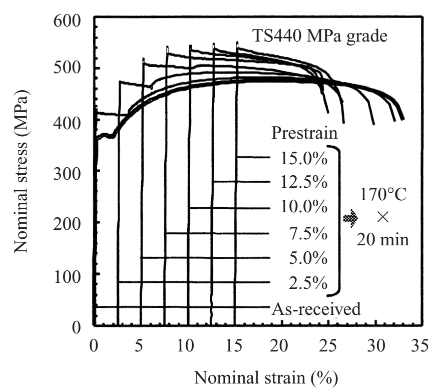

Fig. 6 Stress-strain curves for TS 440 MPa grade BHT steel with different amount of prestrain after strain aging

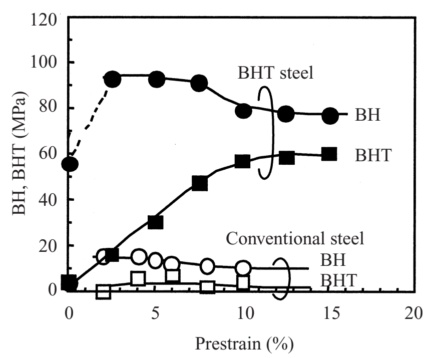

Fig. 7 Effect of prestraining on BH and BHT values for BHT steel after strain aging (t = 1.4 mm)

prestrain to BHT sheets by uniaxial tensioning.

With the conventional steel sheet, both BH and BHT are low, and virtually no increase in strength due to paint baking can be observed. In contrast, with the developed steel, BH shows a high value of approximately 100 MPa with 2% prestrain, while BHT, namely, tensile strength, also shows a remarkable increase. This combination of properties, and particularly the great increase in TS, is the most revolutionary feature of BHT. Although the increase in TS basically reaches saturation at prestrain levels above 10%, BHT increases with prestrain up to the 10% level, showing a value of approximately 60 MPa with 10% prestrain.

Photo 2 shows the effect of paint baking on the TEM microstructure of the BHT steel sheet after the tensile test. Photo 2 (a) shows the results of TEM observation when an additional 4.5% strain was applied after paint baking a BHT steel sheet with 10% prestrain. Photo 2 (b) shows the case when deformation (strain) of 14.5% was applied without paint baking. In the paint-baked material, dislocation loops and tangling of dislocations can be clearly observed, and it can be understood that the dislocation density has increased, whereas, in the non-paint-baked material, the dislocation density is low even though the material was subjected to the same amount of strain. This is thought to be because the dislocations introduced by prestrain were firmly fixed by solid solution elements during paint baking, and as a result, multiplication of new dislocation was accelerated during plastic deformation after paint baking. The external force necessary for multiplication of dislocation increases with the strength of dislocation fixing at dislocation origins, and furthermore, the external force necessary for movement in dislocation groups where dislocations have multiplied also increases with dislocation density. Because stress increases during plastic deformation, it is thought that the increase in tensile strength observed after plastic deformation is due to these two factors.

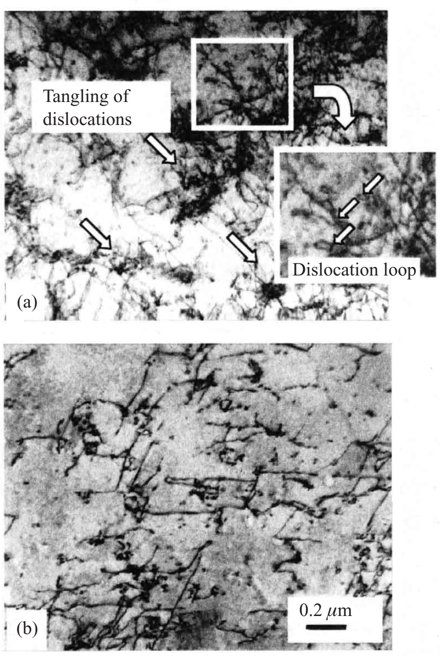

Photo 2 TEM images showing dislocation networks induced by tensile strain with or without baking treatment in BHT steel (a) 10% prestrain → 170°C-20 min baking → 4.5% strain, (b) 14.5% strain

As described above, the newly developed BHT steel sheet makes it possible to secure a large increase in strength stably by paint baking after press-forming.

3.2 Properties and Applications of BHT Steel Sheet

BHT steel sheet shows an increase of approximately 60 MPa in tensile strength due to strain age hardening in addition to work hardening. Improved fatigue characteristics and crashworthiness can be expected as a result of this improvement in TS.

Figure 8 shows the *S-N* curve of a TS440 MPa grade BHT steel sheet in a plane bending fatigue test with and without strain aging. With paint baking at 170ºC $\times$ 20 min after 10% prestrain, fatigue strength increased by approximately 60 MPa in all regions from the low cycle to the high cycle region. The fatigue limit of the as-produced sheet was 221 MPa, but this increased to 276 MPa after strain aging. At the same time, the ductility ratio also increased from 0.44 in the as-produced sheet to 0.50 after strain age hardening, showing that fatigue properties improve remarkably as a result of strain aging.

To evaluate crashworthiness, high strain rate deformation characteristics were investigated in a high strain rate tensile test at a strain rate of approximately 2 000 s^{-1}. The test was performed with an as-produced sheet and a sheet which was subjected to paint baking at 170ºC $\times$ 20 min after 10% prestrain, and absorbed energy was calculated by integrating the stress values up to 15% strain. **Figure 9** shows the effect of paint baking on absorbed energy during high strain rate deformation. With the as-hot-rolled sheet, absorbed energy increases as the TS of the as-produced sheet increases, and the BHT steel sheet shows the same correlation as the conventional sheet. On the other hand, with paint baking after 10% prestrain, absorbed energy and the TS of the as-produced sheet also show a positive correlation, but the BHT steel sheet shows high absolute values in comparison with the conventional sheet.

With the conventional sheet, absorbed energy increases by approximately 10 MJm^{-3}, mainly due to work hardening. In contrast, with BHT steel sheet, absorbed energy increases by approximately 16 MJm^{-3}

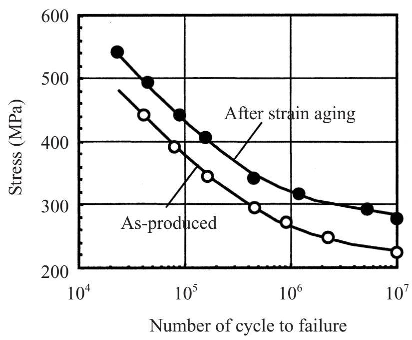

Fig. 8 Influence of strain age hardening on fatigue strength for BHT steel

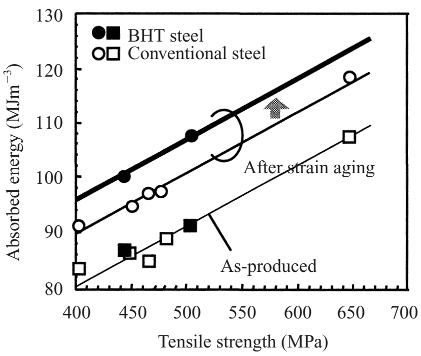

Fig. 9 Comparison in absorbed energy under high strain rate tensile testing between BHT steel and conventional steel

due to the contribution of increased strength attributable to strain age hardening in addition to work hardening. When converted to the increase in the tensile strength of the as-produced sheet, this contribution of strain age hardening to the increase in absorbed energy corresponds to approximately 60 MPa. This shows that the increase in tensile strength (BHT) measured in the tensile test described previously is also manifest as a similar effect during high strain rate deformation.

According to the results of a study of the crashworthiness improvement effect of applying BHT steel sheets to auto parts by FEM analysis based on the data from these tests,[15] the contribution of the strain age hardening of BHT steel sheet is equivalent to a half-gauge (0.1 mm) reduction in the thickness of the hot-rolled sheet or an increase of 60–70 MPa in tensile strength. Thus, it has been shown that BHT steel sheet can contribute to weight reduction by reduction of material thickness, or to securing formability in hard-to-form parts by reduction of the material strength level in press-forming.

Conventional steel sheets with a strain age hardening property have the problem of deterioration of mechanical properties when held at room temperature. In contrast, even when BHT steel sheets are held at room temperature for 1 year, virtually no change is observed in TS, and changes in other properties are also minimal, with YS showing an increase of approximately 30 MPa and El, a reduction of 2% at most. Because segregation of solute N to the grain boundaries is observed in BHT steel sheet, it is assumed that the amount of N in grains is reduced by increasing the grain boundary area by grain refinement, and as a result, room temperature aging was suppressed.

This paper has mainly described the features of TS440 MPa grade BHT steel sheet. However, JFE Steel has already completed the development of a BHT sheet product line ranging from TS370 MPa to TS590 MPa grade based on the same principle, and can also manufacture these products as galvannealed sheets.

Application of BHT steel sheets makes it possible to improve the fatigue characteristics and crashworthiness of automobiles without increasing body weight, or alternatively, reduce body weight while maintaining the same level of fatigue characteristics and crashworthiness, and is therefore expected to contribute to solving environmental problems and improving reliability and safety, which are required in suspension and chassis parts. Further expansion in the applications of the developed steel to automobiles is expected in the future.

4. Conclusion

This paper has introduced two new high-performance high strength steel sheets developed by JFE Steel for critical safety parts of automobiles, and particularly the suspension and chassis, with the aim of contributing to auto body weight reduction and securing crashworthiness.

(1) "NANOHITEN" is a new precipitation-hardened high strength hot-rolled steel sheet in which the precipitates are refined to the size of several nanometers, giving the material an excellent balance of high elongation and a high hole-expansion ratio.
(2) "BHT steel sheet" is a new strain-aging type high strength hot-rolled steel sheet which makes it possible to increase tensile strength substantially by paint baking.

In addition to the excellent properties, these two high strength steel sheets are also extremely original in terms of their steel sheet microstructures, the means of achieving those microstructures, and their metallurgical principles. From this viewpoint, they raise new expectations for future progress in steel materials for automobile bodies, as well as the prospect of achieving high performance and improved reliability in auto bodies by using steel materials.

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