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Hot Rolled High Strength Steels for Suspension and Chassis Parts "NANOHITEN" and "BHT® Steel"†

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Abstract:

Since hot rolled steel sheets for automobile suspension and chassis parts are frequently formed by burring, materials for these applications must possess hole expansionability as well as high strength. "NANOHITEN" is a type of precipitation hardened steel with a soft ferrite single phase matrix and ultra-fine carbides of single nanometer size which successfully satisfies both strength and hole expansionability requirements. "BHT® steel" achieves a very large increase in tensile strength in baking treatment utilizing the strain aging effect of N, which has a high solubility limit. As a result, strength after forming is on virtually the same level as when conventional materials with higher strength levels are used.

1. Introduction

Strength and rigidity are generally required in automobile parts. However, suspension and chassis parts must also meet durability-related requirements, including fatigue characteristics, corrosion resistance, and other properties. Therefore, unlike the auto body, which is made largely from cold rolled steel sheets, mainly heavy gauge hot rolled steel sheets are used in chassis applications. Moreover, as automobile weight reduction has proceeded, high strength materials with tensile strength of 440–590 MPa class have also been increasingly adopted in chassis applications, replacing mild steel.

On the other hand, due to restrictions in the suspension layout and the need to avoid interference between parts under large inputs, chassis and suspension part shapes have tended to become more complex, and composite forming involving stretch-forming and stretch-flanging techniques such as burring, etc. are frequently used in the manufacture of these parts. Hole expansionability and elongation are required in these forming modes. However, it is known that these two properties are generally mutually contradictory in steel sheets.

Dual-phase (DP) steels sheets and low alloy retained austenite (TRIP) steel sheets are known to show high elongation. However, since these steels are characterized by a large difference in hardness between the main phase, which consists of soft polygonal ferrite, and the hard second phase of martensite, etc., it was difficult to increase hole expansionability because of voids form at the interphase between these phases during punching. To remedy this problem, bainite single phase and bainitic ferrite single phase steel sheets have been developed in order to reduce the hardness difference between the main and second phases, but it cannot be said that the balance of strength and hole expansionability is adequate, particularly in materials with tensile strength of 780 MPa class and higher. As additional problems, due to heavy use of Si, a type of surface roughness called "red scale" and internal oxidation are remarkable, resulting in reduced fatigue characteristics and phosphatability/corrosion resistance[1)].

This paper introduces two new high strength hot rolled steel sheets which are suitable for automobile suspension and chassis parts, (1) "NANOHITEN," a precipitation hardened high strength hot rolled steel sheet

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in which precipitates are refined to the single nanometer level, thereby satisfying both high hole expansionability and high elongation requirements, and (2) “BHT® Steel,” a strain aging-type high strength hot rolled steel sheet which shows dramatically increased tensile strength after baking treatment.

2. Precipitation Hardened High Strength Hot Rolled Steel Sheet “NANOHITEN”

2.1 Strengthening Mechanism and Features of “NANOHITEN”

NANOHITEN (NANO: New Application of Nano Obstacles for Dislocation Movement) is a type of high tensile strength steel which satisfies both the above-mentioned hole expansionability and elongation requirements. In this innovative product, the steel sheet is strengthened using precipitates refined to single nanometer size. Its features are as follows.

(1) Single phase microstructure using ferrite with excellent formability as the matrix.
(2) Strengthening by precipitates refined to single nanometer size.
(3) Extremely high thermal stability of precipitates.
(4) Due to the extremely large strength increment achieved by precipitation hardening, it is possible to avoid use of Si as a solid solution hardening element.

A schematic diagram of the effect of the microstructure on the balance of elongation and hole expansionability is shown in **Fig. 1**. With multi-phases such as ferrite + martensite (F + M), high elongation is obtained while hole expansionability is low; conversely, with single phase microstructures such as bainite single phase steel, hole expansionability is high while elongation is low. Noting the high elongation of ferrite and the high hole expansionability of single phase microstructures, in NANOHITEN, hole expansionability is improved while maintaining high elongation by using a ferrite single phase microstructure. However, with conventional

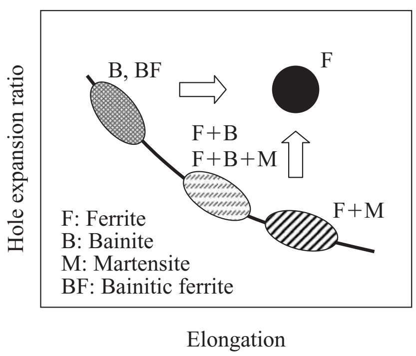


Fig. 1 Effect of microstructure on elongation and hole expansion ratio

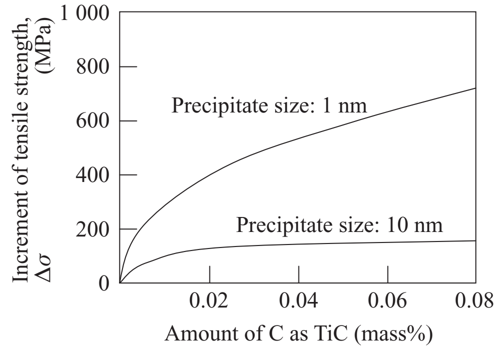


Fig. 2 Effect of size and amount of precipitates on the increment of tensile strength

methods, it is not easy to achieve strength of 780 MPa or higher with ferrite single phase steels.

Figure 2 shows the results of a calculation of the relationship between the amount of precipitates and the increment of precipitation hardening in conventional precipitation hardened steel with precipitates having sizes of 10 nm and 1 nm, assuming the Orowan-Ashby mechanism[2]. Because the strength increment is determined by the spacing of the precipitates, the effect of precipitate size increases with the precipitate content. For example, when the amount of C precipitated as TiC is 0.08 mass%, it is possible to achieve precipitation hardening of 700 MPa if the size of the precipitates is refined to 1 nm. Based on this result, the aim in NANOHITEN was to maximize the precipitation hardening effect by refining precipitates to the single nanometer size. However, if precipitates are fine but thermally unstable, coarsening can easily occur due to variations in manufacturing conditions, inviting reduced strength and strength deviations. For this reason, thermal stability is required in the precipitates.

Therefore, in NANOHITEN, innovations were applied in order to refine the precipitates to the single nanometer size and, furthermore, to improve their thermal stability. Concretely, focusing on X-Y-C ternary carbides, various combinations of X and Y were studied. As a result, it was discovered that extremely fine precipitates are precipitated in a system in which appropriate amounts of Ti and Mo are added to a 0.04C-1.3Mn steel base[3].

Photo 1 shows the results of SEM observation of the microstructure of NANOHITEN and TEM observation (dark field image) of the precipitates. The matrix is a ferrite single phase, and a large number of ultra-fine precipitates with a size on the order of 3 nm have precipitated in rows. The results of EDS and X-ray diffraction confirmed that these precipitates are (Ti, Mo) C and have a lattice constant (0.431 nm) which is virtually identical with that of TiC. From observation results including reflected dark field images and others, it is considered that these precipitated coherently while maintaining the

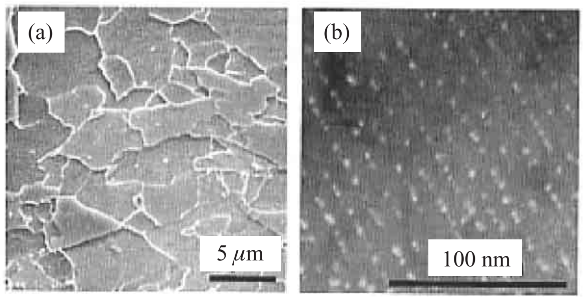


Photo 1 Microstructure(a) and precipitates(b) of NANOHITEN

Baker-Nutting relationship with the matrix, in the same manner as TiC.

Figure 3 shows the results of measurements of the decrease in tensile strength (ΔTS) at room temperature after NANOHITEN and conventional precipitation hardened steel using TiC were reheated to 650°C followed by isothermal holding. When the conventional steel sheet using precipitation hardening by TiC is held for 15 × 10^3 s, a large decrease in tensile strength accompanying coarsening of the TiC can be observed, but in contrast, with NANOHITEN, in which precipitation hardening is achieved mainly with (Ti, Mo) C, there is virtually no decrease in tensile strength after holding for 80 × 10^3 s. Thus, it can be understood that the precipitates in NANOHITEN have extremely high thermal stability[4]. When NANOHITEN was held at high temperatures of 700°C and above and the size of the coarsened (Ti, Mo) C and atomic concentration ratio of Ti/Mo were measured, results like those shown in **Fig. 4** were obtained. This suggests that Ti is the controlling diffusion element, and in fact, it has been confirmed experimentally that coarsening of precipitates is suppressed by reducing the solution of Ti[5].

The hot rolling process used in manufacturing NANOHITEN is virtually unchanged from the ordinary process for manufacturing general steel grades, and a precipitation hardened ferrite single phase microstructure is obtained at a coiling temperature similar to that used with general steels. If conventional precipitation hardened steels are coiled at such high temperatures, pearlite frequently forms, but with NANOHITEN, a ferrite single phase microstructure is obtained stably since the C content is reduced and Mo, which suppresses the pearlite transformation, is added. In addition, unlike multi-phase steels and conventional precipitation hardened steels, which are prone to strength variations depending on coiling conditions, deviations in tensile strength are extremely small in NANOHITEN due to combination of the ferrite single phase microstructure and stability of the precipitates. This means that changes in the amount of spring back during press forming are minimal.

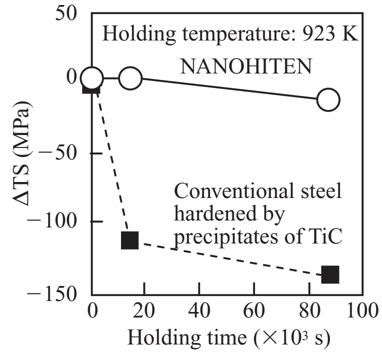


Fig. 3 Comparison of the thermal stability of strength between NANOHITEN and conventional HSLA steel

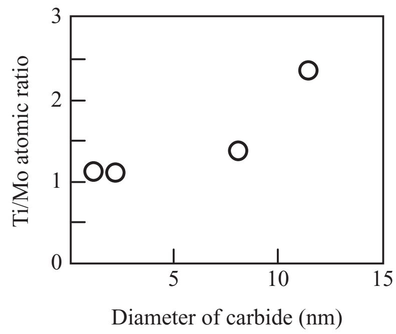


Fig. 4 Change in Ti/Mo atomic concentration ratio of (Ti, Mo)C with coarsening

Furthermore, since the large strength increase attributable to the NANO precipitates occurs in the coiling process after hot rolling, 780 MPa grade NANOHITEN is soft during hot rolling, being equivalent to 540 MPa–590 MPa grade steel. This makes it possible to produce thin products with the thicknesses of less than 1.8 mm and wide sheets exceeding 1 000 mm, which had been difficult with the conventional 780 MPa grade steel.

2.2 Properties and Condition of Application of NANOHITEN

A comparison of the typical chemical composition and mechanical properties of 780 MPa grade NANOHITEN and those of a conventional high stretch-flangeability-type high strength hot rolled steel sheet is shown in **Table 1**. NANOHITEN has an extremely good balance of elongation and hole expansionability in comparison with the conventional steel. This is considered to be an effect of the “ferrite single phase” and “ultra-fine precipitates” mentioned above as features (1) and (2), respectively.

Extremely high yield strength (YS), which is obtained as another effect of ultra-refinement of the precipitates, is also an advantage of NANOHITEN. Since YS is the controlling factor for bending crushing strength, which corresponds to a side collision in an automobile, and furthermore, NANOHITEN can be manufactured in the form of thin hot rolled sheets and

Table 1 Typical chemical composition and mechanical properties of NANOHITEN and conventional high barring steel in TS 780 MPa grade

	Chemical composition (mass%)				Mechanical properties			
	C	Si	Mn	Others	YS (MPa)	TS (MPa)	El (%)	λ (%)
NANOHITEN	0.04	Tr.	1.4	Ti, Mo	745	805	20	100
Conventional high barring steel	0.07	0.99	1.54	Ti	696	810	18	79

YS: Yield strength, TS: Tensile strength, El: Elongation,
λ: Hole expansion ratio

used as material for hot dip galvannealed sheets, as discussed in the following, the potential uses of NANOHITEN are not limited to chassis parts, but also include auto body structural parts.

On the other hand, a composition design without Si addition, which was mentioned as feature (4), has the effect of improving surface quality.

In general, addition of Si becomes necessary when the strength of a steel sheet exceeds 590 MPa class, but since Si concentrates at the surface, phosphatability is reduced. However, the phosphatability of NANOHITEN, which is completely Si-free, is substantially the same as that of mild steel.

There are also cases in which scale marks (roughness) called "red scale" occur on Si-added steels. This is caused by the oxidized layer of Si which concentrates at the surface. **Figure 5** shows the relationship between the fatigue limit in a plate bending fatigue test and the TS of the base material for the respective types of hot rolled steel sheets. The fact that the increase in the fatigue limit is slightly relative to the increase in base material strength when TS exceeds 590 MPa is attributable to this type of surface roughness. Because red scale does

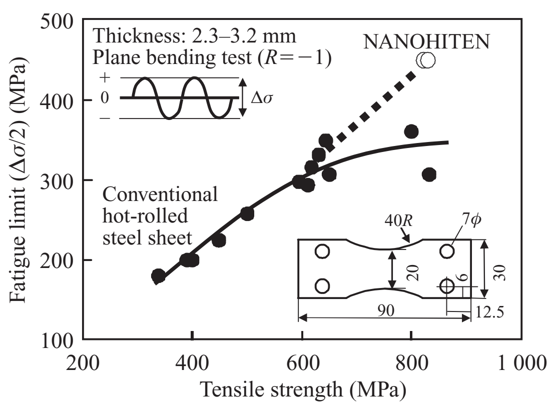


Fig. 5 Comparison of the fatigue limit between NANOHITEN and conventional high strength low alloy (HSLA) steel

not occur in NANOHITEN, as it does not contain Si, an increase in the fatigue limit corresponding to strength can be expected.

Taking advantage of the fact that NANOHITEN is Si-free, it is also possible to use this steel as material for hot dip galvannealing after hot rolling. Based on the fact that "precipitates are stable at high temperature," as mentioned in feature (3), the mechanical properties of NANOHITEN after galvannealing are virtually unchanged from those after hot rolling. Since C addition is reduced by maximizing precipitation hardening, spot weldability and other types of weldability are excellent and hardening of welds is slight. Thus, NANOHITEN is also advantageous for application to tailor welded blanks (TWB).

Based on the features described thus far, 780 MPa grade NANOHITEN is being progressively adopted in auto body structural part and safety parts, etc., in addition to underbody parts such as chassis and arm parts. This product is currently in mass production exceeding 1 000 t/month, and an expanded range of applications is expected in the future. Although this paper has introduced 780 MPa grade, the NANOHITEN product line also includes 980 MPa grade and sheets for hot dip galvannealing, enabling users to select materials corresponding to the property requirements of parts.

3. Strain Aging-Type High Strength Hot Rolled Steel Sheets "BHT Steel"

3.1 BHT and Its Mechanism

BHT steel (BHT: Bake Hardenable Steel with Tensile Strength Increase) is a completely new type of hot rolled high tensile strength steel sheet in which tensile strength is increased by forming baking treatment in the part of manufacturing process[6–10].

Conventional "BH steel" has been well known from an early date. These are steel sheets in which yield strength is increased after forming/baking treatment using the strain aging effect of solute C, and are widely used to improve dent resistance, mainly in outer panels. As a distinctive feature of BHT steel, use of N, which has a high solubility limit in comparison with C, improves not only yield strength, but also tensile strength.

Since solute N will be lost if AlN precipitates in the cooling process after hot rolling, precipitation of AlN is suppressed in BHT steel by controlling cooling conditions. In conventional products, the fact that solute N tends to cause aging deterioration was a problem, however in BHT steel, diffusion/migration of N at room temperature was successfully prevented by refining the crystal grain size by rapid cooling after hot rolling and

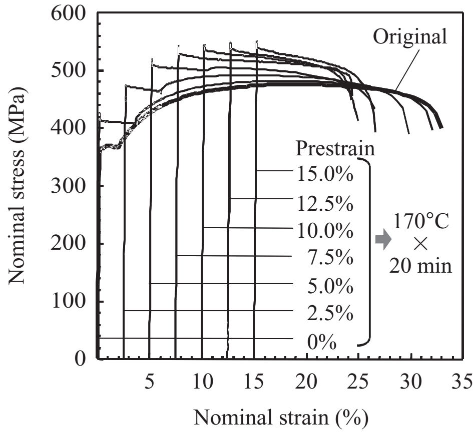


Fig. 6 Stress-strain curves of TS 440 MPa grade BHT steel with different amount of prestrain after strain aging

segregating solute N to the grain boundaries.

Figure 6 shows the stress-strain curves of BHT steel after strain aging. In comparison with conventional BH steel, it can be understood that BHT steel shows increased tensile strength in addition to a large increase in yield strength after aging. The increase in tensile strength can greatly improve the fatigue characteristics and the impact-absorbing capacity, as discussed in the following.

Figure 7 shows the effect of prestrain on the BH value and BHT value when prestrain of 0–15% was applied to BHT steel by uniaxial tensile, followed by baking treatment at 170°C × 20 min in an oil bath, in comparison with conventional steel. Here, the "BH value" and "BHT value" mean the increments of yield strength and tensile strength due to baking treatment, respectively.

In all cases, the BH value and BHT value of the conventional steel are low, and virtually no increase in strength can be seen as a result of baking. In contrast, with 2% prestrain, the BH value of BHT steel is high, at approximately 100 MPa, and the BHT value is also high. In other words, TS increases remarkably. The BHT value increases with prestrain and shows a value of approximately 60 MPa at 10% prestrain. The change in the BHT value when prestrain is increased above 10% is saturated.

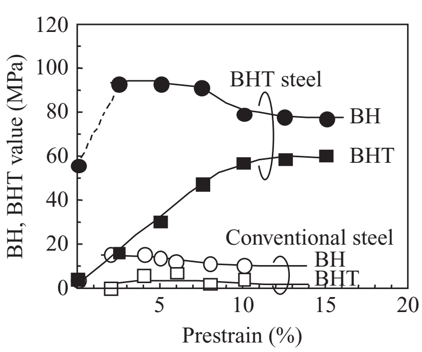
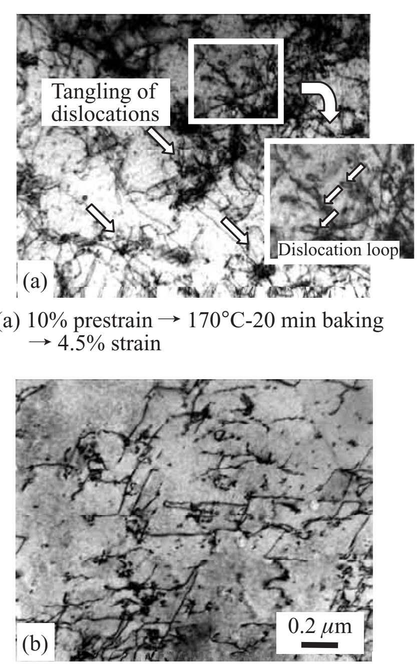


Fig. 7 Effect of prestrain on BH and BHT value for BHT steel after strain aging (t = 1.4 mm)

The mechanism responsible for the BHT phenomenon is based on the pinning of dislocations by solution atoms, which can also be observed in conventional BH steels. However, in BHT steel, it is considered that the pinning force is stronger, resulting in a larger BH value in comparison with the BH steels, and this also acts advantageously on subsequent multiplication of dislocations.

Photo 2 shows the effect of baking treatment on the TEM microstructure of BHT steel after a tensile test. Photo 2(a) shows the result of TEM observation after applying 10% prestrain, baking treatment, and additional 4.5% strain. Photo 2(b) shows the case when deformation up to 14.5% was applied without baking treatment. In the material with baking treatment, dislocation loops and dislocation tangles can be clearly observed, and it can be understood that the dislocation density has increased. On the other hand, the dislocation density of the material without baking treatment is low, even though the total amount of deformation is the same. This is considered to be because the dislocations which had been introduced by prestrain were firmly pinned by solution atoms during baking treatment, and consequently, multiplication of new dislocations was promoted during plastic deformation after baking treatment. The external force necessary for multiplication of dislocations increases as dislocations are more firmly pinned at the



(a) 10% prestrain → 170°C-20 min baking → 4.5% strain

(b) 14.5% strain

Photo 2 TEM images showing dislocation networks induced by tensile strain with or without baking treatment in BHT steel source of the dislocation, and the external force necessary for movement of dislocations within dislocation groups which have multiplied increases with the dislocation density. It is thought that tensile strength increases since these phenomena cause increased stress during plastic deformation.

As described above, with BHT steel, it is possible to secure a large strength increase stably by baking treatment after press forming.

3.2 Properties and Condition of Application of BHT Steel

The typical chemical composition and an example of the mechanical properties of 440 MPa grade BHT steel are shown in **Tables 2** and **3**, respectively, in comparison with conventional TS440 MPa grade hot rolled steel. The formability of the base material is completely unchanged from that of the conventional steel. **Figure 8** shows the width of open wedge (*W*) due to spring back, in other words, shape fixability. It can be understood that the TS-W relationship of the BHT steel base material lies on the same line as that of the conventional steel sheet[11].

With BHT steel, tensile strength increases by approximately 60 MPa due to strain aging hardening in addition to work hardening. Therefore, improved fatigue characteristics and crashworthiness in comparison to conventional steels can be expected after aging treatment.

Figure 9 shows the relationship between the fatigue limit (FL) and TS of BHT steel before and after 10% prestrain + aging treatment at 170°C × 20 min[11]. With both BHT steel and conventional steel, FL increases from that of the base material as a result of prestrain + aging treatment. However, the FL of BHT steel after aging treatment is approximately 40 MPa higher than that of the conventional steel. It has also been confirmed that this improvement is not limited to FL. After aging treatment, fatigue strength in the low cycle region is also higher than in the conventional steel, and the increase is proportional to TS.

The following presents the results of a comparison/evaluation of absorbed energy during high speed deformation in high strain rate tensile testing by the Hopkinson pressure bar method. **Figure 10** shows a comparison of absorbed energy with BHT steel and the conventional steel, which was calculated by integrating the stress at 15% strain on a stress-strain curve at a strain rate of approximately 2 000 s^{-1} obtained by this method[11] . Both BHT steel and the conventional steel showed an increase

Table 2 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 3 Typical mechanical properties of TS 440 MPa grade BHT steel

(t = 1.4 mm)

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

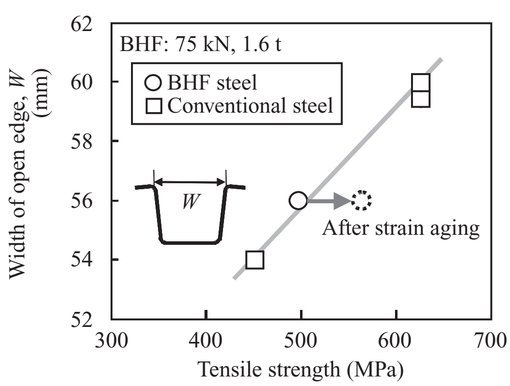


Fig. 8 Shape fix-ability of BHT steel compared with conventional steel

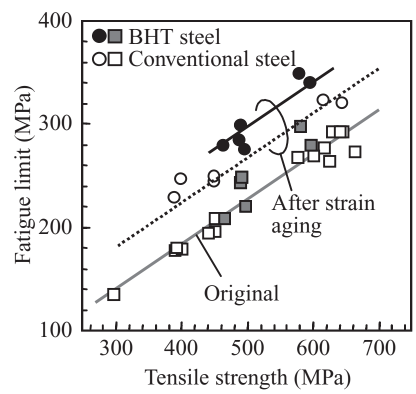


Fig. 9 Fatigue Limit of BHT steel compared with conventional steel

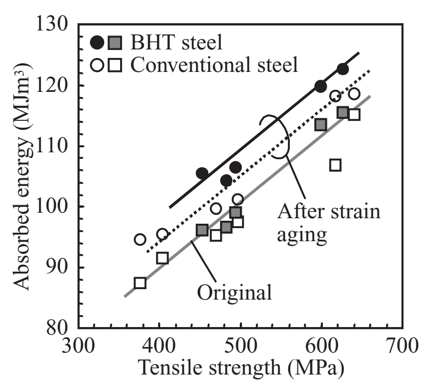


Fig. 10 Absorbed energy at high strain rate tensile testing of BHT steel compared with conventional steel

in absorbed energy as a result of 10% prestrain + aging treatment at 170°C × 20 min. However, the absorbed energy of the BHT steel after strain aging treatment was approximately 5 MJm^3 higher than that of the conventional steel, confirming that there is a larger absorbed energy increase effect with BHT steel. The effectiveness of BHT steel has also been confirmed in a drop weight test of trial-manufactured parts, and FEM analysis[12] based on the data from these tests showed that it is possible to achieve a weight reduction of 0.1 mm by sheet thickness conversion, which is equivalent to a half gauge in hot rolled steel sheets.

Since the FL and absorbed energy of BHT steel after 10% prestrain + strain aging treatment at 170°C × 20 min described above correspond to the increase in TS by prestrain + strain aging treatment, it is possible to explain these as effects of BHT. In other words, these results show that use of BHT steel makes it possible to obtain performance after forming/baking equal to that of conventional steel with 60 MPa higher MPa tensile strength, while also obtaining the same formability as the conventional steel during forming.

With conventional steel sheets having a strain aging property, deterioration of mechanical properties due to holding at room temperature is generally a problem. In contrast, even when held at room temperature for 1 year, BHT steel shows extremely small changes in properties. Specifically, there is virtually no change in TS, YS increases by approximately 30 MPa, and El decreases by at most 2%. As discussed previously, grain boundary segregation of N due to grain refinement has been confirmed in BHT steel, and this is thought to contribute to stabilization of solute N at room temperature.

Taking advantage of these features, application of 440 MPa BHT steel to the front side member, lower arm, and other parts in which fatigue strength or crashworthiness is required is progressing.

This paper has focused on BHT steel with a base material strength of 440 MPa grade, which is equivalent to 590 MPa grade after forming. However, based on the same principle, JFE Steel has completed a full product line of BHT steels in the range of base material strengths from 370 MPa grade to 590 MPa, and also produces hot dip galvannealed sheets.

Application of BHT steel makes it possible to increase fatigue characteristics/crashworthiness without increasing auto body weight, or to reduce body weight while maintaining the same level of fatigue characteristics/crashworthiness, and is expected to contribute to reliability, safety, and solution of environmental problems, which are required in suspension and chassis parts.

4. Conclusion

This paper has introduced two high performance high strength steel sheets which are suitable for realizing weight reduction and securing crashworthiness in the automobile body, particularly in parts that are important for safety, such as suspension and chassis parts, (1) “NANOHITEN,” a precipitation hardened-type high strength hot rolled steel sheet with a combination of high elongation and high hole expansionability, which is achieved by refining precipitates to the single nanometer level, and (2) “BHT steel,” a strain aging-type high strength hot rolled steel sheet that makes it possible to increase tensile strength by baking treatment. In addition to the properties obtained, these two high strength steel sheets are also extremely original in terms of the sheet microstructure, the means of achieving the microstructure, and the metallurgical principles involved. Expanded application is expected in the future.

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