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Metallurgical Features of NANOHITEN^{TM} and Application to Warm Stamping†

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Abstract:

NANOHITEN^{TM} in 780 MPa grade of tensile strength has achieved excellent stretch flange formability as the same level of 440 MPa grade with ferrite grains strengthened by nanometer-sized carbides. Uniform fine carbides in NANOHITEN^{TM} are dispersed into ferrite grains by interphase-precipitation phenomena. The diameter of the fine carbides became 1/10 compared with the conventional TiC, and the amount of precipitation-strengthening increased to 300 MPa. Since fine carbides in NANOHITEN^{TM} are hardly coarsened, NANOHITEN^{TM} is suitable to warm stamping. Experimental results of warm stamping indicated that warm stamped NANOHITEN^{TM} with 980 MPa grade showed good formability at the same level of cold stamped high strength steel with 590 MPa grade.

1. Introduction

Heavy gauge hot-rolled steel sheets and cast parts are used in automobile chassis parts (e.g., suspensions and frames). In addition to strength and stiffness, durability-related properties such as fatigue resistance, corrosion resistance, etc. are required. In order to reduce the weight of these chassis parts, steel sheets with thicknesses of 2.6–4 mm and tensile strength of 440–590 MPa class are now generally used. Because the stretch-flange formability of the steel sheet is particularly important when chassis parts are formed by press-stamping, development of materials with higher stretch-flange formability is continuing.

Although improvement of the phase ratio and hardness distribution in low alloy steel (TRIP steel) sheets containing retained austenite and dual phase steel (DP steel) sheets, which are known to show high elongation, have been applied in order to obtain good stretch-flange formability, none of these efforts has arrived at a fundamental solution. Bainitic steel and bainitic ferrite single phase steels have also been developed, but it is difficult to realize high strength, particularly tensile strength of 780 MPa class and higher. Moreover, even assuming that stretch-flange formability is improved, negative effects, such as a remarkable decrease in elongation, are unavoidable. Thus, numerous practical problems remain to be solved.

In contrast, JFE Steel developed a new high strength hot-rolled steel sheet named NANOHITEN^{TM}, which is suitable for chassis parts, based on a completely new concept of microstructure design. NANOHITEN^{TM} is a high strength hot-rolled steel sheet with a microstructure consisting of ferrite grains in which ultra-fine, nanometer-sized carbides are dispersed, and displays mechanical properties different from those of conventional multiphase high strength steel sheets, represented by DP steel sheets and TRIP steel sheets, which consist of a ferrite phase and a hard phase. This unique feature is not limited to the original target of application to chassis parts. Use of NANOHITEN^{TM} in body parts is also considered to be possible.

This paper describes this new technology, focusing mainly on 780 MPa class NANOHITEN^{TM}, and then discusses development to higher strength materials and warm stamping, and also touches on expansion of applications from chassis parts to body parts.

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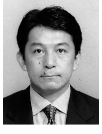

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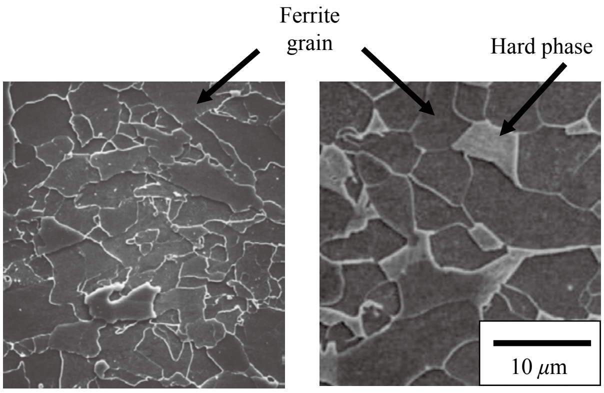
2. Features of NANOHITEN^{TM}

2.1 Microstructure of NANOHITEN^{TM}

NANOHITEN^{TM} (NANO: New application of nano obstacles for dislocation movement)[1] is a steel sheet which is strengthened by using nanometer-sized carbides to harden the ferrite grains. Its features are as follows.

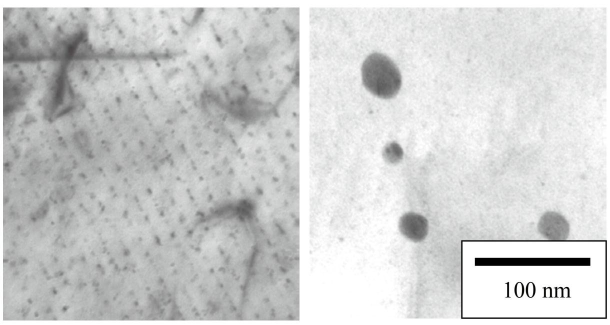
(1) Single phase microstructure of ferrite with excellent formability.
(2) Strengthened by carbides refined to a size of several nanometers.
(3) Carbides resist coarsening even when heated.
(4) Because high strength is achieved by precipitation-strengthening, an alloy design without addition of solid-solution strengthening elements such as Si, etc. is possible.

As a comparison with the microstructure of NANOHITEN^{TM}, a scanning electron micrograph of a conventional high strength steel sheet is shown in **Photo 1**. In the conventional high strength steel sheet, high strength is achieved by dispersing a hard phase of martensite in the ferrite matrix. In contrast, only ferrite grains, which have high formability, are observed in NANOHITEN^{TM}. Furthermore, the ferrite grains in NANOHITEN^{TM} are fine in comparison with those of the conventional high strength steel sheet.



(a) NANOHITEN^{TM} (b) Dual phase steel

Photo 1 Scanning electron micrographs showing microstructures



(a) NANOHITEN^{TM} (b) Conventional precipitation-strengthened steel

Photo 2 Transmission electron micrographs showing carbides

The following describes the nanometer-sized carbides which are used to achieve high strength in NANOHITEN^{TM}. The strength of ferrite microstructures which do not fine contain carbides, for example, mild steel, is only about 300 MPa in tensile strength. This is strengthened up to 780 MPa class by nanometer-sized carbides dispersed in the ferrite grains. A transmission electron micrograph of the carbides in the ferrite grains of NANOHITEN^{TM} is shown in **Photo 2**. For comparison, the photo also shows the carbides in a conventional high strength steel sheet. The carbides in NANOHITEN^{TM} are shown by the contrast of dots with a size of several nanometers, which can be observed aligned in a row-like form from the upper left to the lower right in the micrograph of NANOHITEN^{TM}. Refinement can be confirmed by comparing the fine NANOHITEN^{TM} carbides with the coarse carbides in the conventional high strength steel sheet, which are several tens of nanometers in size. The fact that the carbides display this row-like form shows interface precipitation of carbides. Interface precipitation is a phenomenon in which carbides precipitate at the interface between the austenite and ferrite phases during austenite-ferrite transformation, and was first reported by Morrison[2].

A transmission electron micrograph when a carbide in NANOHITEN^{TM} was observed at a higher magnification is shown in **Photo 3**. As the carbide has a disk-shaped morphology, Photo 3 was observed from the [110] direction of matrix, which is the thickness direction of the disk. The carbide exists in the Baker-Nutting[3] relationship with the ferrite crystal, namely, (001) carbide // (001) ferrite, <100> carbide // <110> ferrite. The atoms mutually at the interfaces between the ferrite and the upper/lower faces of the disk-shaped carbide have a one-to-one correspondence, and thus form a type of interface termed coherent.

A schematic diagram showing that high strength is

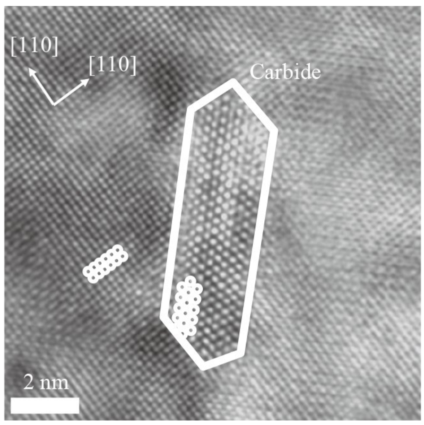


Photo 3 Transmission electron micrographs showing carbide in NANOHITEN^{TM}

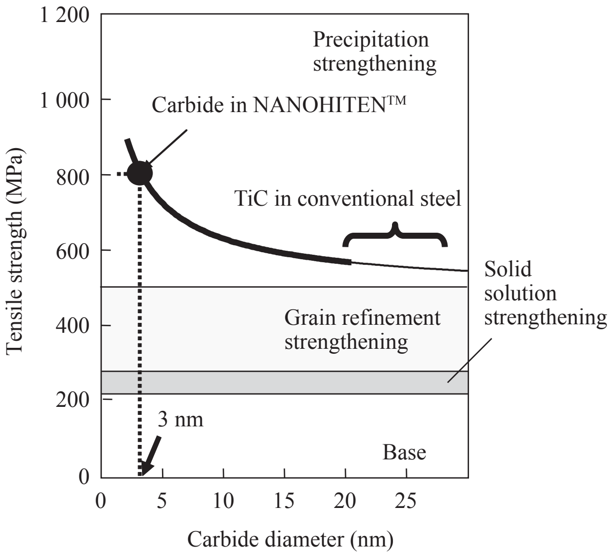


Fig. 1 Schematic diagram of relationship between amount of tensile strength and carbide diameter

obtained by carbide refinement to the above-mentioned nanometer-size carbides is shown in **Fig. 1**. In calculations of the amount of strengthening, yield strength was calculated assuming the Ashby-Orowan equation[4)] and an empirical equation for solute strengthening proposed by Pickering[5)]. Tensile strength was then calculated assuming a yield ratio of 0.9. In Fig. 1, only precipitation strengthening on the order of 100 MPa could be obtained with the carbides precipitated in the conventional high strength steel sheet, but in contrast, precipitation strengthening of NANOHITEN™ was high, at 300 MPa, and high strength of 780 MPa class in tensile strength was realized.

It is thought that fine carbides generally undergo remarkable coarsening by Ostwald ripening. However, in spite of the ultra-fine size of the carbides of NANOHITEN™, these carbides show no significant coarsening under heating.

This technology by using carbides formed by 2 or more kinds of carbide-forming elements is realized for the first time; carbides formed by a kind of carbide-forming element, as exemplified by the conventional TiC or NbC[6)] are used in the conventional steels. **Figure 2** shows room temperature hardness after holding at 650°C for NANOHITEN™ and a steel in which fine TiC was dispersed in the same manner as in NANOHITEN™ by applying the ideal thermal history in the laboratory. Virtually no decrease in the hardness of NANOHITEN™ can be observed, even after holding at 650°C for 24 h. In contrast, the hardness of the TiC strengthened steel decreased remarkably. From this result, it is clear that the nanometer-sized carbides of NANOHITEN™ resist coarsening even when heated.

2.2 Formability of NANOHITEN™

In conventional multiphase high strength steel sheets, stretch-flange formability decreases remarkably at higher strength levels. This is attributed to the larger volume percentage of the hard phase which is used to achieve high strength. A schematic diagram explaining this condition is presented in **Fig. 3**. Here, the hole expanding ratio, which is included in the standards of the Japan Iron and Steel Federation, is used as an index of stretch-flange formability. In the hole expanding test, a punched hole is opened in the specimen steel sheet before hole expanding. However, voids are generated at the interface between the ferrite and hard phase when punching is performed, and during the following process of hole expanding, cracks are easily generated by linkage of these voids. In order to improve the hole expanding ratio, it is necessary to suppress the formation of voids. Reducing the hardness ratio of the ferrite phase and hard phase is effective for achieving high hole expanding ratio[7)]. Since NANOHITEN™ does not contain a hard phase, it is considered that an excellent hole expanding ratio can be obtained because the hardness of the hypothetical hard phase is identical with that of the ferrite phase.

Since NANOHITEN™ possesses excellent formability, as described above, application of 780 MPa class material to chassis parts is being promoted. This high

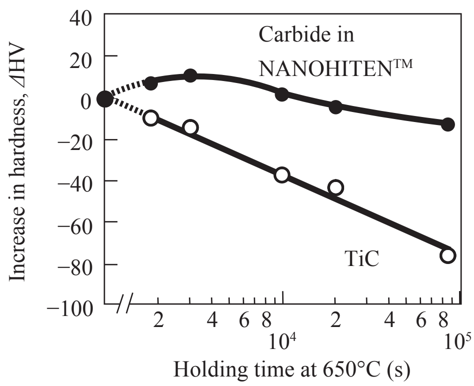


Fig. 2 Change in hardness of sample after holding at 650°C

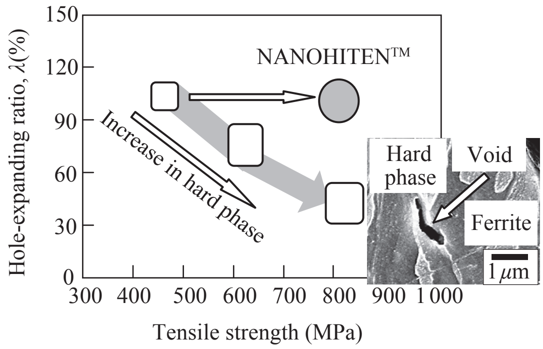


Fig. 3 Change in hole-expanding ratio of dual phase steel with increase in tensile strength and that of NANOHITEN™

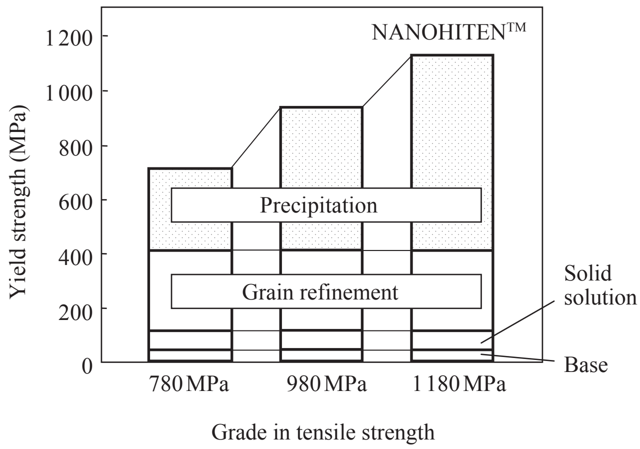


Fig. 4 Change in precipitation-strengthening with increase in tensile strength

strength NANOHITEN™ has already been applied to multiple types of automobiles, and has made an important contribution to weight reduction.

2.3 Realizing Higher Strength in NANOHITEN™

As high strength is realized in NANOHITEN™ by fine carbides, higher strength can be obtained by increasing the content of carbides. **Figure 4** shows a schematic diagram of strengthening from 780 MPa to 980 MPa and 1 180 MPa. The y-axis is yield strength, and shows the breakdown of the increment of strengthening at each strength level. High strength up to the 1 180 MPa class was successfully realized by increasing the amount of precipitation strengthening.

Furthermore, NANOHITEN™ has excellent hot-rolling properties because the amount of solution strengthening elements is reduced. As a result, it is possible to manufacture sheets with thicknesses of 2 mm and less, even in high strength hot-rolled steel sheets. By applying NANOHITEN™ with the high yield strength shown in Fig. 4, for example, 1 180 MPa class NANOHITEN™, to automobile frame components, it is possible to obtain absorbed energy in bending collapse on the same level as that of hot stamped materials.

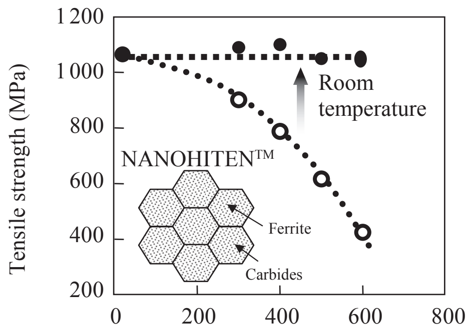
Chapter 3 presents examples of application of a special warm stamping technology using NANOHITEN™ to automobile frame components.

3. NANOHITEN™ Warm Stamping Technology

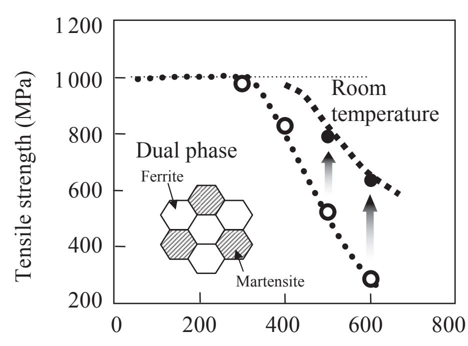
3.1 Warm Stamping Technology and NANOHITEN™

Warm stamping is a technology in which a steel sheet is heated from approximately 200°C to around 700°C before pressing-forming (“stamping”), and then is immediately pressed with a die. Accordingly, it is a distinctive feature of this technology that stamping can be performed with a lower press load than that in cold stamping because the sheet is stamped while in a heated condition. Application of hot stamping has expanded in recent years. However, warm stamping does not require die cooling to the same extent as in hot stamping, and for this reason, the lower dead point which is necessary in hot stamping is not required in warm stamping. This eliminates the need of special press machines, and also increases productivity. Warm stamping technology is already being used in the field of light metal sheets, such as stainless steel sheets and aluminum alloy sheets, in which phase transformation dose not become a problem. If applied to the conventional type high strength steel sheets, the microstructure would be changed by the heating process before pressing, and it would not be possible to obtain the required strength. Therefore, warm stamping could not be performed with the conventional type of high strength steel sheets.

In Chapter 2, Fig. 2 showed that the room temperature strength of NANOHITEN™ is not reduced by heating. In other words, if the carbides of NANOHITEN™ are used, warm stamping of high strength steel sheets becomes possible. Therefore, as a simulation of warm stamping, the tensile strength of steel sheets at each temperature was measured. The room temperature tensile strength of steel sheets after heated to each temperature



(a) NANOHITEN™



(b) Dual phase steel

Fig. 5 Tensile strength at high temperatures and at room temperature after deformation and subjected to 5% strain are also measured. The sheets used in this experiment were 980 MPa class NANOHITEN™ and a conventional 980 MPa class multiphase high strength steel sheet (980DP). In both cases, the sheet thickness was 1.6 mm. The relationship between the deformation temperature and strength is shown in **Fig. 5**. With NANOHITEN™, tensile strength decreased with the increase of the deformation temperature, and room temperature strength after deformation maintained the original strength. At the same time, elongation was the same as that of the base material, revealing that applied strain is relaxed by warm stamping. On the other hand, with the conventional multiphase steel sheet, although the decrease in tensile strength with the increase of the deformation temperature was similar to that of NANOHITEN™, room temperature strength after deformation also decreased. This is attributed to the progress of tempering of the martensite phase.

From these results, it can be concluded that NANOHITEN™ is a high strength steel sheet that is suitable for warm stamping, and thus is a material which did not exist in the past.

3.2 Warm Stamping Property of NANOHITEN™

In cold stamping of high strength steel sheets, spring-back and twist easily become issues. On the other hand, because the press load is reduced in warm stamping of NANOHITEN™, reductions in the spring-back and twist can be expected. First, hat-shaped parts were produced by the warm stamping of NANOHITEN™, and the difference between the size of the punch and the pressed part was measured. For comparison, the difference was also measured when multiphase cold-rolled sheets of each strength level were cold stamped with the same die. The stamping method was form molding, and the sheet thickness of the base materials was 1.6 mm. A stamping rate of 20 stamps per minute (spm) was used. The relationship between the strength of the steel sheet and the difference between the size of the punch and the pressed part is shown in **Fig. 6**. When 980 MPa class NANOHITEN™ was stamped at 500°C, the difference was the same as that of the cold-stamped steel sheet with tensile strength of 700 MPa class, and when 980 MPa NANOHITEN™ was stamped at 600°C, the difference was on the same order as that of the cold-stamped 590 MPa class high strength steel sheet which are currently used.

Next, the amount of twist generated in actual warm stamping using a model die of a center pillar will be discussed. The shape of the model die of the center pillar and the method of measuring twist are shown in **Fig. 7**. The difference between the shape of the die and the shape of the part when using the respective dies is shown in **Fig. 8**. Although 980 MPa class NANOHITEN™ showed larger twist than the 590 MPa class high strength steel sheet when the NANOHITEN™ material was cold-stamped, these results clarified the fact that twist was substantially identical to that of the 590 MPa high strength steel sheet when 980 MPa class NANOHITEN™ was warm-stamped at 600°C.

Based on these results, if NANOHITEN™ is used, it is considered possible to apply high strength materials of 980 MPa class and higher to parts in which high

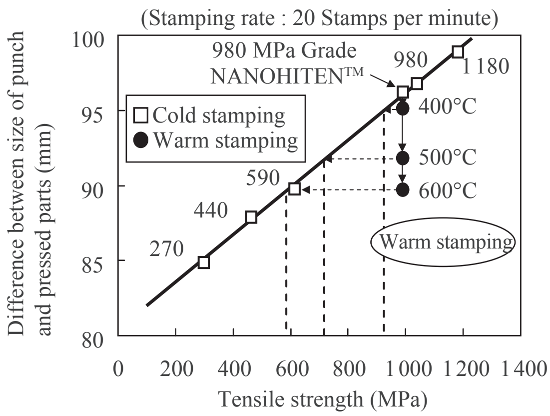


Fig. 6 Change in difference between size of punch and pressed parts with tensile strength

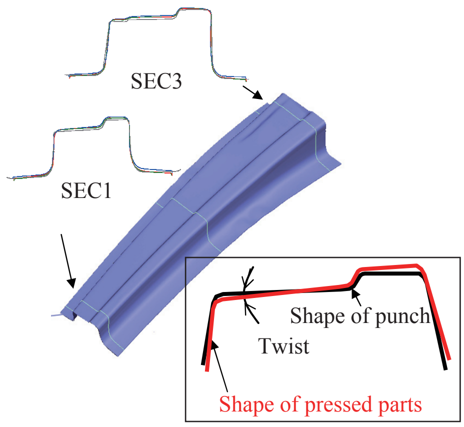


Fig. 7 Schematic illustration of model parts of center pillar

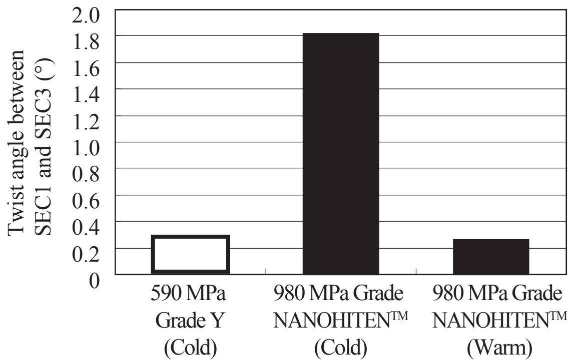


Fig. 8 Actual twist angle of model parts

strength materials could not be used previously due to the problem of shape. Furthermore, by applying high yield strength NANOHITEN^{TM} to auto frame components, it is possible to obtain high component strength and high impact absorbed energy. For example, by using 1 180 MPa class NANOHITEN^{TM}, it is considered possible to obtain the same absorbed energy as with hot stamped components. Considering these advantages, progress in the adoption of high strength materials in automotive parts is expected by applying NANOHITEN^{TM} in combination with warm stamping technology.

4. Conclusion

This paper introduced the features of NANOHITEN^{TM} steel sheets, and showed that NANOHITEN^{TM} is a high strength steel sheet which is suitable for warm stamping. NANOHITEN^{TM} is a steel which was developed based on the new concept of using ultra-fine carbides to strengthen the ferrite grains. Thus, as a single phase material with no hard phase for strengthening, NANOHITEN^{TM} exhibits excellent formability. Expanded application of high strength steel sheets to hard-to-form parts can be expected by applying warm stamping, taking advantage of the features of NANOHITEN^{TM}, and it is considered that this will contribute to automobile weight reduction.

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