UDC 629 . 11 . 011 : 669 . 14 . 018 . 26

Technical Review

Development of Advanced High Strength Sheet Steel for NSafe™-AutoConcept

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Abstract

The NSafe™-AutoConcept project was conducted to produce a light weight car with enhanced crashworthiness and body rigidity by integral approaches from materials, forming technologies and structural studies. Steel products constitute the principal material used in an automobile structure. In this report, advanced high strength sheet steels recently developed at Nippon Steel Corporation and their basic microstructure and mechanical properties are reviewed.

1. Introduction

Auto manufacturers are continuously confronted with the need to further reduce car body weight and enhance crash safety, and at the same time, to respond to the requirements for electric vehicles, conversion to new energy sources, and automated driving in an environment in which substantial social and industrial changes are taking place. Nippon Steel Corporation regards such major changes of the automotive industry as the starting point of new business evolution, and has developed NSafe™-AutoConcept. First, the requisites for a future automobile and its components are estimated. Second high-value-added measures for an entire automobile are proposed by integral approaches to materials, forming technologies and structural studies.

A common passenger car has a mass of roughly one thousand kilograms, and steel accounts for nearly 70% of it. Car body weight is reduced by decreasing the thickness of the materials used, but it is necessary, on the other hand, to maintain crash safety and sufficient body stiffness. For this reason, it is essential for car weight reduction to enhance the performance of the materials. The present paper describes the characteristics required for different car parts and introduces various types of steel sheet products for automotive applications. Future considerations on material development are also presented.

2. Fundamental Characteristics of Iron & Steel and Development of Sheet Steels for Automotive Applications

Figure 1 compares various materials in terms of density and Young's modulus; the materials are arranged in the order of atomic number. Density changes periodically with the increase in atomic number. This is because density is affected by the atomic mass as well as crystal structure, and the manner in which atoms are arrayed in space. Iron (Fe) is positioned at a peak of the periodical change of density, which means that its density is higher than other materials of neighboring atomic numbers. In terms of Young's modulus, on the other hand, the absolute value of iron is comparatively higher than that of the others, which indicates that iron is excellent in rigidity. Young's modulus reflects interatomic bonding strength, and the high density and Young's modulus of iron means that iron has a

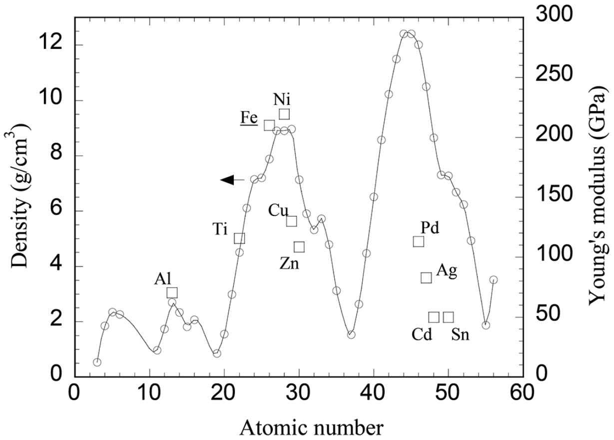

Fig. 1 Relationship between density and Young's modulus of various materials

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closely packed crystal structure. Although aluminum is widely studied as a promising material for car body weight reduction, Young's modulus of iron is nearly three times that of aluminum. Since the density of iron is roughly three times that of aluminum, iron and aluminum are substantially the same in terms of specific rigidity.

At present, sheet steels for automotive application are available in a wide range of tensile strength grades from 270 MPa to more than 1.8 GPa. **Figure 2** schematically shows the relationship between strength and elongation of the material used for automobile parts. Originally, the sheet steels for automotive application used to be of mild steel having a low carbon content and ferrite structure, enabling a 270 MPa class tensile strength and an excellent elongation exceeding 40% to be obtained. The strength of this all-ferrite structure has been increased by measures such as solid solution hardening, precipitation hardening, structural strengthening with hard structures, etc. As a general rule, elongation tends to decrease with increasing strength, and for this reason, the strength-elongation bands in Fig. 2 slope downward toward the right. Looking at aluminum alloys and magnesium alloys, of which the use for automotive applications is being studied, they are found in lower strength regions than sheet steels.

Most aluminum alloys now used for automobiles have a tensile strength of roughly 300 MPa, and in terms of tensile deformation, it is possible with high strength steels of 980 MPa grade or higher to achieve a greater weight reduction than with such aluminum alloys. In actual automotive applications, what is required is not tensile strength alone, but also other strength properties in different deformation modes such as bending. In bending mode, its strength increases in proportion to the n-th power ($n \fallingdotseq 2$) of sheet thickness. Thus, the usage of a thicker sheet with low density materials becomes advantageous to increase bending strength. In other words, in order to make maximum use of steel materials, which feature a substantial ability for strengthening shown in Fig. 2, optimal designs of structural parts should be anchored not by in-bending forces but by in-plain forces such as tension and/or compression. To this end, it is important to develop sheet steels having such good formability that it realizes such a structure with real automobile parts, and a forming method adequate for the properties of such a material; studies are being conducted in this direction.

Sheet steels for automotive applications are used in quantities for panels, body structure, chassis parts, etc., but their types have

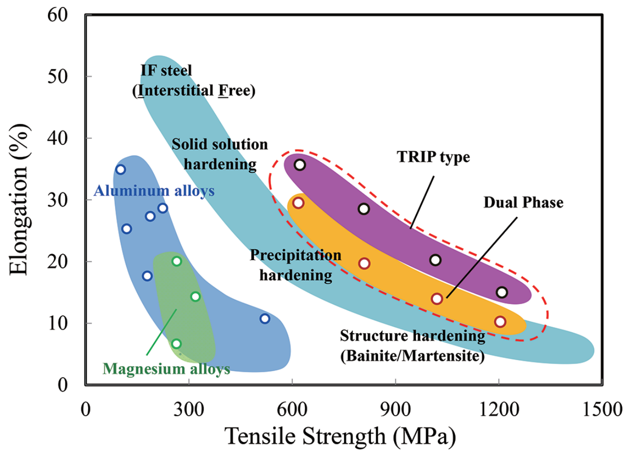


Fig. 2 Relationship between tensile strength and elongation in various materials

changed significantly since the late 1990s.[1, 2] This is because, in response to increasingly stricter regulations of crash safety and higher targets of fuel economy to reduce CO_2 emission, the substitution of conventional steels with other of higher strength steels has been intensively studied. More recently, types of steel having yet higher strength than high strength steels (ultra-high strength steels) have been developed, and actually applied to cars in the market.

Of the different types of high strength and ultra-high strength steels available, the one most widely used for automotive parts is dual-phase steel (often called DP steel) given in Fig. 2. Originally, DP steel was produced by having ferrite and austenite in a temperature range where the two phases can coexist, and then rapidly cooling them into a combined structure of ferrite and martensite. Recently, however, steels of complicated structure containing other structures (bainite, for example) are considered to be new varieties of DP steels. The mechanical properties of DP steel are characterized by a comparatively low yield strength (or yield ratio), and excellent elongation. The strength of DP steel is often discussed in relation to hard martensite, and the low yield strength and good elongation in relation to soft ferrite.

Another type of steel containing austenite, which is stabilized in its production so as not to transform at room temperature, is called transformation-induced-plasticity (TRIP) steel. It is characterized by high elongation due to austenite's transformation into martensite due to plastic deformation. Steel materials having tensile strength exceeding 1 GPa and excellent in elongation are being eagerly sought in many countries. Such researches aim at obtaining new types of steel with excellent properties at realistic costs through the elaboration of steel chemistry and optimizing steel producing processes. Those target steel types are often collectively called the third-generation advanced high strength steel.[3] Most of these attempts are to increase the percentage of retained austenite. However, when carbon and manganese are added in large quantities as alloying elements to take advantage of retained austenite, in-use properties typically such as weldability are adversely affected. As far as the automotive applications are concerned, it is necessary to realize desired properties within a certain limit of chemical compositions.

A wide variety of sheet steels have been developed for different automobile parts by considering fundamental material characteristics. Presently, as part of the activities of NSafe™-AutoConcept, Nippon Steel is proposing steel solutions for drastic weight reduction of automobiles. To conceive such proposals, it was necessary to clarify the in-use properties of individual parts, and incorporate the required characteristics in sheet steels for such parts. The basic philosophies on how to realize such material characteristics in individual products are explained below.

3. High Strength Steels for Automobile Body Structure

3.1 Automobile body structural parts and required material properties

The properties required for the materials for body structure can be understood from two main aspects. One is strength: the strength of body structure, typically such as impact absorption capability, can be enhanced by increasing material strength, and the advantage of the increase in body strength can be utilized for weight reduction, too. The other is formability: in cold forming such as stamping, formability is required in deep drawing, stretch forming, stretch flanging, bending, etc. depending on the shapes and manufacturing methods of the parts.[4] Formability is also important for the resist-

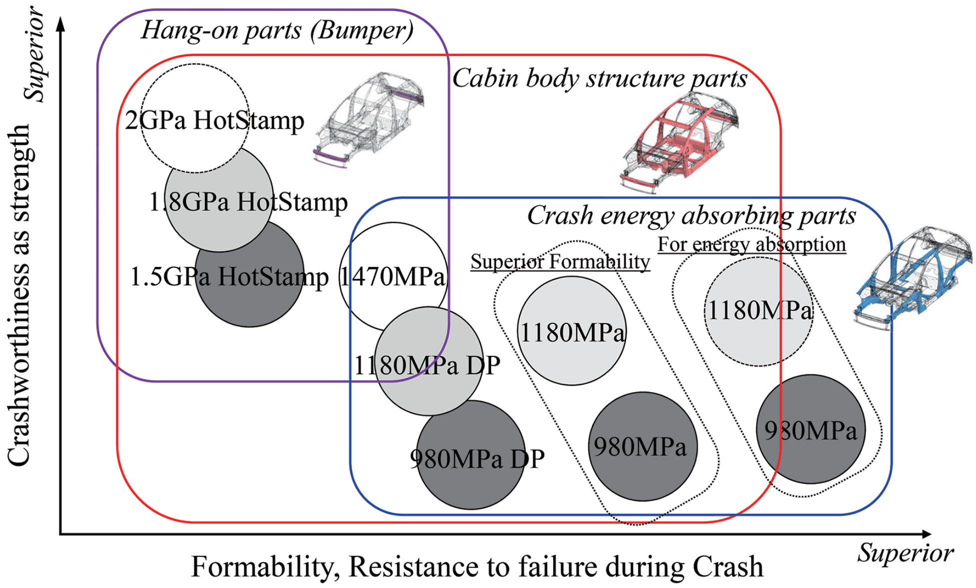


Fig. 3 Evolution of high strength sheet steels for automobile body structure

ance to failure during crash after the material sheets are made into parts of definitive structures. **Figure 3** illustrates the evolution of high strength steels for automobile body structure by using the axes of strength and formability.

In Fig. 3, which includes many types of sheet steels, the body structural parts can be classified into three large groups from the viewpoints of strength and formability. The first is what is known as hang-on parts typically such as bumpers. Use of high strength steels is most advanced for this group. Hot stamping is widely employed for manufacturing these parts, and hot stamping steel of 1.8 GPa grade has been developed and commercially applied over the last few years. The details of this new product are presented later herein.

The second group of body parts immediately following the hang-on parts in terms of application of high strength steels is the parts for cabin structure. Presently, hot stamping steel of a 1.5 GPa grade and high strength steels for cold forming of a 1 180 MPa grade are used for these parts. In the activities for NSafe™-AutoConcept, through comprehensive studies on materials, forming technologies and structural studies, Nippon Steel is proposing extensive use of a 1 470 MPa grade high strength steel for many structural parts of this group.

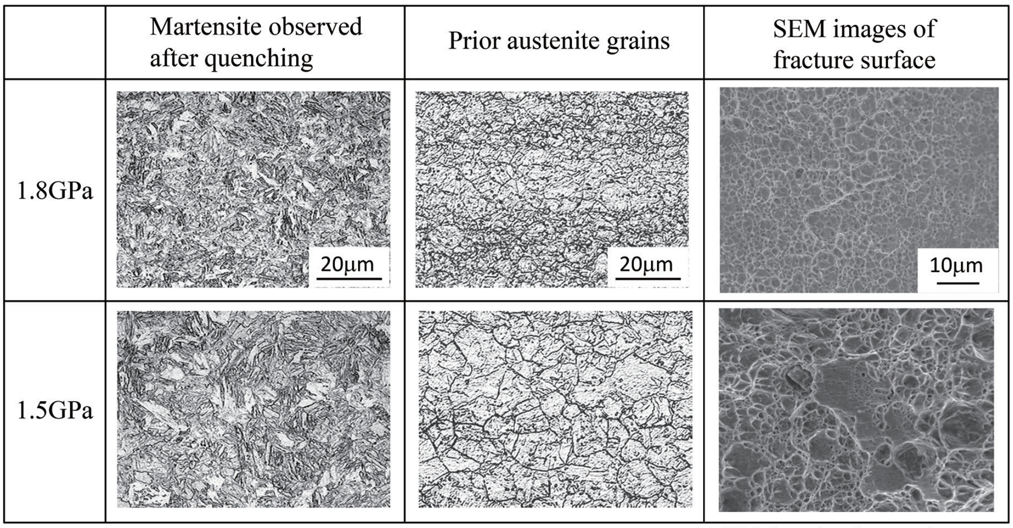
The third group comprises the structural parts positioned at the front and the rear of the cabin such as front and rear side members. These parts have the function to absorb crash impact energy at frontal or rear collision by large deformation through axial collapsing or bending. The materials for these parts are required to have adequate strength for both body weight reduction and crash energy absorption, and in addition, to exhibit excellent formability that will not fail during large deformation and to avoid an abrupt change of parts deformation (mainly buckling) modes. Looking back at the history of the advanced high strength steels for automotive parts, the first application of steels with higher strength began with the first group, the hang-on parts. Then, it was expanded to the cabin structural parts, and then, to the parts for absorbing large impact energy. In the latest automobile structure, sheet steels of 590 to 780 MPa grades are widely used for the parts of the third group.

3.2 Evolution of advanced high strength steels for body structure

Hot stamping is commercially employed in the manufacture of body structural parts having a strength of 1.5 GPa or more.[5)] The method is excellent in that parts with ultra-high strength can be obtained without having material failure and dimensional inaccuracy, which are the main problems of cold forming. The process consists of heating a sheet to roughly 900°C to have austenite single phase stamping of it into a desired shape, and then quenching it between the tools to transform austenite into martensite. Since the stamping is done at high temperatures, the stamping force is low, and because the martensite transformation compensates the residual stress caused by stamping, the dimensional accuracy of the parts is favorable.[6)]

In addition to the conventional hot stamping steel of a 1.5 GPa grade, Nippon Steel has launched to the market a 1.8 GPa grade hot stamping steel.[5)] High strength is mainly ensured by martensite for hot stamping steel. Although the strength of martensite increases with the carbon content, high carbon content leads to low toughness, and desired properties may not be obtained. **Figure 4** compares the microstructure after quenching of the developed hot stamping steel of 1.8 GPa grade with that of a conventional 1.5 GPa hot-stamping steel. Both microstructures exhibit lath martensite. The prior austenite grain size of the 1.8 GPa grade is smaller. Looking at the fracture surfaces after the tensile test, the fracture mode of the 1.8 GPa grade was ductile fracture, and the dimples were finer than those of the 1.5 GPa grade. This steel was confirmed to have high toughness, weldability and good resistance to hydrogen embrittlement while exhibiting the desired strength of 1.8 GPa.[5)] To achieve yet higher strength levels, Nippon Steel is developing new hot stamping steels having a strength of 2 GPa or higher, as seen in Fig. 3.

Regarding high strength steels for cold forming, it has already been explained herein that ductility, such as tensile elongation is improved by a combination of several microstructures, typically found in DP or TRIP steels. When hard and soft structures coexist, deformation is distributed within the material in a complicated manner. **Figure 5** shows results of in-situ observations by a laser microscope during tensile deformation of a 590 MPa grade DP steel. Corre-



SEM: Scanning electron microscope

Fig. 4 Comparison of microstructures between 1.5 and 1.8 GPa grade hot-stamping steels

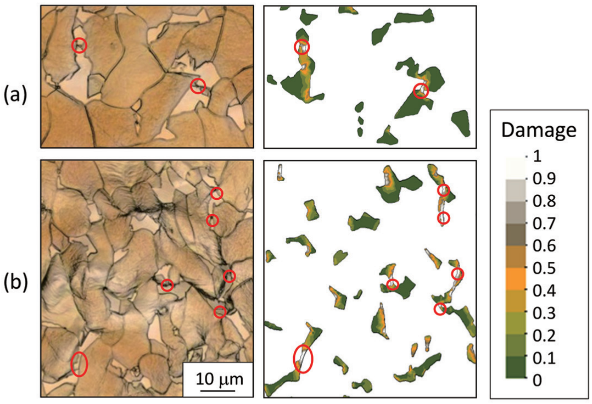


Fig. 5 In-situ observations of martensite fracture and its comparison with numerical simulations ((a) 0.1 strain, (b) 0.28 strain)

sponding results of numerical simulations are also shown in Fig. 5.[7] Here martensite is colored in white and ferrite in brass by etching. At 0.1 strain, plastic deformation concentrates at the narrows of martensite grains, and failures are beginning to occur there (marked with red circles). Further, at 0.28 strain, the number of failures increases, and ferrite surfaces begin to roughen, which seems to demonstrate that a large deformation is taking place.

As seen above, during tensile deformation, high elongation is realized by deformation of soft structures surrounding hard structures, making up for its low formability. However, in the case where the positions at which deformation concentrates are limited such as bending, the material is likely to fail in an early stage if there exist hard structures there. In consideration of this, different types of 980 MPa grade steels have been developed and made available for different applications; such include a bending type product having a homogeneous matrix, and an elongation type having martensite dispersed in a matrix of ferrite, which is excellent in ductility.[8, 9]

Several parts for cabin body structure and crash energy absorbing areas sometimes have complicated shapes, and when they are to be made of high strength steels, the material must be excellent in formability as well as in strength, and soft ferrite or retained austenite, which exhibits the TRIP phenomenon, has to be used. **Figure 6** shows an example of the microstructure of an 1180 MPa grade high-formability high strength steel for cold forming.[10] The microstructure consists of ferrite, martensite/bainite, and austenite, 1 μm or less in size; this steel is reported to have both high ductility and excellent stretch-flangeability (bendability). The high material performance is ascribed to the extremely fine structures obtained thanks to adequate selection of chemical compositions and processing conditions.

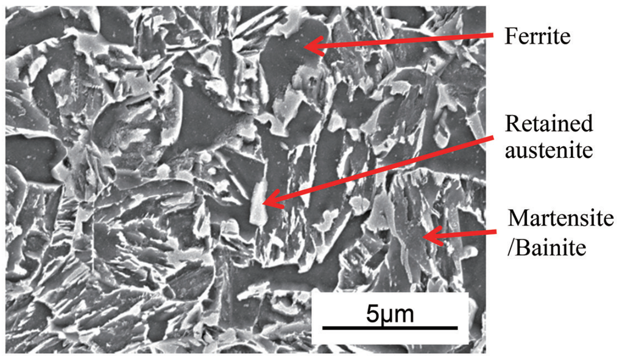


Fig. 6 Microstructure of 1180 MPa grade high strength steel with enhanced elongation

For the crash energy absorbing parts, in addition to good formability, it is necessary is to avoid an abrupt change of parts deformation modes due to the fracture at the deformation concentrated area. While the steels used for these parts are mostly 590 to 780 MPa grades or lower as stated earlier, it has become clear lately that steel grades of yet higher strength can be used when adequate structural design is employed.

Figure 7 shows an axially crushed specimen of 1180 MPa grade high strength steel with an adequate cross-sectional design.[11] This specimen of 1180 MPa grade steel enables the energy absorption capacity to increase 1.6 times greater than that of the 590 MPa grade steel specimen with the square cross section, while the weight is reduced by 30%.[11] Through close examination of the buckled posi-

Fig. 7 Axially crushed specimen of 1 180 MPa high strength steel for energy absorbing parts

tion, the mode of deformation was found to be bending. Actually, one type of 1 180 MPa grade steel excellent in bending behavior was selected for this specimen, which was one of the reasons for the high impact absorbing capacity. As seen in Fig. 2, ultra-high strength steels of 980 MPa tensile strength or more have a lower ductility (elongation) than that of mild steel. However, by improving the specific functions and performance of ultra-high strength steels (bending behavior, for instance) required for the target parts, further reduction of car body weight should become feasible by appropriate material substitutions.

4. High Strength Steels for Chassis Parts

Many chassis parts are critical safety-related parts, and require high reliability in terms of strength, stiffness, durability, corrosion resistance, etc. Since chassis parts are mostly made of thicker steels than other kinds of automotive parts, hot-rolled steels are used for many of them. The material strength is mostly of a 440 MPa grade, but steels of 590 and 780 MPa grades are also used, and further developments with even higher strength are currently in motion.

High strength hot-rolled steels for chassis parts are required to be excellent in both stretch formability (closely related to the elongation at tensile tests) and stretch flangeability (typically such as the burring of joints with bushings of lower arms). When ferrite, which is soft and excellent in elongation, is combined with hard phases, the hard phase grains fracture and/or voids developed at their boundaries deteriorate formability such as stretch flangeability under large plastic deformation (see Fig. 5). Making microstructure homogeneous is effective at improving stretch flangeability, and therefore, chemical compositions and production conditions are selected so that the final microstructures of this application are bainite single phase structure or a mixture of ferrite and bainite with similar hardness. Because coarse cementite precipitates greatly deteriorate stretch flangeability, it is preferable to have dispersed fine cementite precipitates or to control carbon content as low as possible.[12]

The properties of the developed 780 MPa grade steel are shown in **Fig. 8**. Its hole-expansion ratio, an indicator of stretch flangeability, is higher than that of conventional steel, and it has good stretch flanging properties and high elongation as well. The developed steel is excellent also in appearance, and has good fatigue resistance.[13]

As stated earlier, if steels of a 980 MPa grade or higher can be used for chassis parts, a weight reduction greater than that by all-

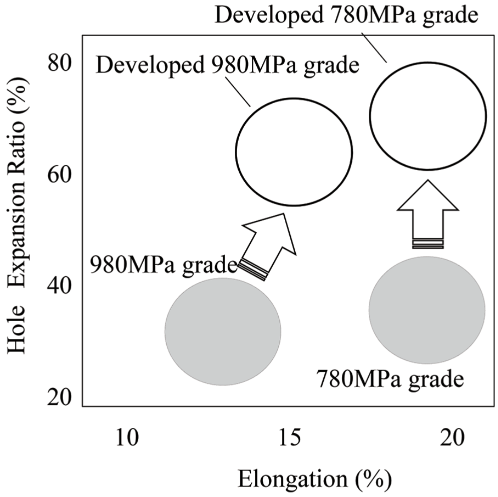


Fig. 8 Mechanical properties of developed 780 and 980 MPa hot-rolled steels

aluminum parts becomes attainable. Steel of a 980 MPa grade excellent in arc weldability as well as bendability and fatigue properties has been made available for truck frame parts. Further, through the control of microstructure and the hardness difference between component structures in the same manner as in the 780 MPa grade, hot-rolled steels of a 980 MPa grade that exhibit higher elongation and hole-expansion ratio are being developed (see Fig. 8).

5. Conclusion

Future prospects mainly from the viewpoint of materials, which have been obtained through the activities for NSafe™-AutoConcept, have been discussed and a new concept for a next-generation automobile by highly utilizing steel products was presented. Steel has a high potential for strengthening, and the exploitation of its potential will lead to further reduction of the car body weight. Nippon Steel is expected to spread its technology fostered in Japan to outside to deploy high-functional products globally, and thus further contribute to the suppression of global warming and enhancement of the crash safety of automobiles.

As a structural material, sheet steels for automotive use has demonstrated unprecedented changes, and as a result, steels twice the strength of that in the 2000s or even higher are being used for some automobile parts. While various problems have been solved concurrently, the advance in this field is characterized by the fact that new application technologies of forming and welding were developed in synchronization with the materials development of new steel grades. Increasingly larger technical hurdles will appear as steel strength is increased, but technical innovation has to continue through combined advances in the fields of steel material itself and the application technologies. The synergistic effects of the technologies of materials development and application technologies are expected to strengthen the automotive industry.

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