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Technical Review

Development of Advanced High Strength Steel Sheets for Autobody Lightweighting

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Abstract

NSafe™-AutoConcept ECO ***³ is a new concept that offers a comprehensive proposal considering weight reduction, environmental response, and economic efficiency towards the realization of a carbon neutral society. The development of advanced high strength steel sheets with excellent properties is essential for its realization. This report reviews the characteristics of steel materials, which are the main materials for automobiles, and provides a technical overview of automotive steel sheets developed by Nippon Steel Corporation in recent years.***

1. Introduction

To achieve carbon neutrality, automobile industries are promoting electrification and adaptation to new energy sources. These changes in powertrain systems have altered the roles of various components in vehicle bodies, leading to the emergence of new parts and the elimination of others. In addition, from the perspectives of crash safety and improved fuel efficiency, weight reduction has long been pursued by applying aluminum alloys and high-strength steel to vehicle body components. In this context, Nippon Steel Corporation proposed the next-generation automotive concept “NSafe™-AutoConcept”,[1] which combines advanced high-strength steel sheets with structural design and manufacturing methods to enhance the overall value of the vehicle. Furthermore, a new concept, “NSafe™-AutoConcept ECO³”, has been introduced to offer optimal solutions that meet customer needs from the perspectives of weight reduction, environmental compliance such as CO_2 emissions, and economic efficiency.

A common passenger car weighs around one ton, with steel accounting for roughly 70% of its mass. Weight reduction can be achieved by using thinner sheet thicknesses for automotive materials, but simultaneously ensuring collision safety and stiffness is essential. Furthermore, automobiles are composed of numerous parts, each serving different functions. Consequently, the properties required of steel sheets vary significantly depending on the application. Therefore, efforts to enhance the performance of automotive steel sheets for body weight reduction have been conducted according to the specific properties demanded by each component. This report describes the characteristics of steels as an automotive material and the developed steels designed to meet the required properties of each component. In addition, future technological prospects are discussed.

2. Characteristics of Iron and Steel as an Autobody Material

The primary factors governing vehicle weight are collision safety and stiffness, which correlate with material strength and Young’s modulus, respectively. In recent years, Life Cycle Assessment has gained prominence as a key metric for assessing carbon neutrality, making greenhouse gas emissions—including CO_2—from material manufacturing and disposal (CO_2 emissions) a critical consideration in material selection. This chapter presents the advantages of using steel materials in automotive applications from the perspectives of strength, Young’s modulus, and CO_2 emissions.[2–4]

2.1 Potential for weight reduction

Figure 1 schematically shows the relationship between specific strength and elongation for various materials. Specific strength is an index for comparing strength under conditions of mass equivalence, calculated by dividing tensile strength by density. At present, steel sheets for automotive applications are available in a wide range of tensile strength grades from 270 MPa to 2.0 GPa. Among these, steel sheets exceeding 980 MPa surpass aluminum alloys in specific strength, offering significant potential for weight reduction. Elongation of materials tends to decrease with increasing strength, but when comparing materials with the same specific strength, steel exhibits higher elongation than aluminum alloys and magnesium al-

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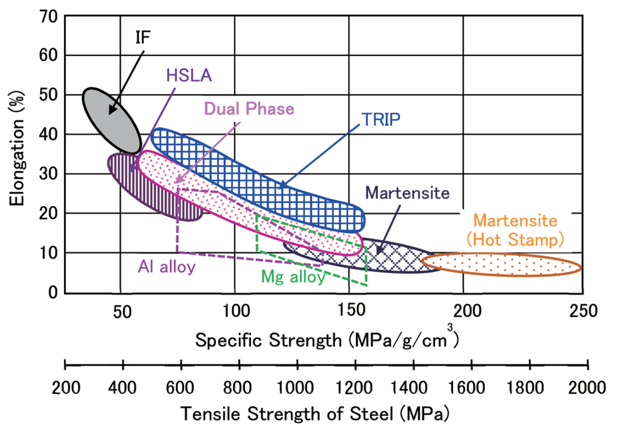

Fig. 1 Relationship between specific strength and elongation in various materials

loys. DP (Dual Phase) steel and TRIP (Transformation Induced Plasticity) steel achieve even higher elongation through optimization of composition and manufacturing processes. This diagram illustrates why high-strength steel sheets are an ideal material for balancing collision safety and weight reduction.

The practical performance of a vehicle body also depends on its rigidity; therefore, specific stiffness—defined as Young's modulus divided by density—is also crucial for weight reduction. The density of iron is 7.87 g/cm^3, about three times that of aluminum, and its Young's modulus is also about 205 GPa, nearly three times that of aluminum. Consequently, the specific stiffness of iron and aluminum is nearly equivalent. In other words, from a stiffness perspective, iron possesses weight reduction potential equivalent to aluminum.

Automotive components undergo various deformation modes besides tensile stress. It is known that bending strength is proportional to the nth power of sheet thickness (n=~2). Therefore, steel has disadvantage in the bending mode. To leverage steel's high specific strength and specific stiffness for weight reduction, it is necessary to combine structures that allow forces to be applied along the plate surface—such as closed sections or continuous flanges—with manufacturing methods that enable these structures.

2.2 Potential for reducing greenhouse gas emissions

In carbon neutrality assessments, CO_2 emissions across the entire lifecycle—from material manufacturing to vehicle disposal—are increasingly emphasized. For automobiles, while driving emissions have historically been the primary focus, with attention on improving fuel efficiency (reducing emissions) through body weight reduction, lifecycle assessment (LCA) also considers emissions from material production and disposal.

Figure 2 shows the results of evaluating CO_2 emissions for steel and aluminum alloy vehicle bodies across the material production, vehicle manufacturing, and vehicle operation.[5)] Approximately two tons of CO_2 are emitted during the production of one ton of steel via the blast furnace process. However, it is significantly less than that used in aluminum refining by the electrolytic process in a comprehensive lifecycle evaluation, it is important to consider CO_2 emissions during material manufacturing. As fuel efficiency regulations and electrification reduce operational emissions, the importance of overall lifecycle reduction increases further. Additionally, steel is easily recoverable and recyclable as scrap after vehicle end-of-life,

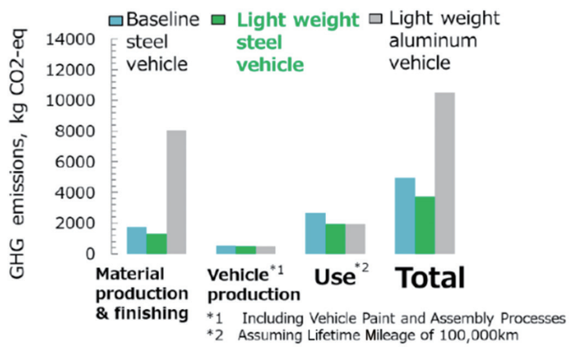

Fig. 2 Result of life cycle GHG emission of body

making it an environmentally favorable material from a lifecycle assessment perspective. While price and properties have traditionally dominated material selection, comprehensive environmental impacts—including CO_2 emissions during material production and recyclability—will likely become key indicators moving forward from a carbon neutrality standpoint.

3. Development of Advanced High-strength Steel Sheets

To Achieve the lightweight vehicle body proposed in the NSafe™-AutoConcept, the development of advanced high-strength steel sheets with superior properties is indispensable. This chapter introduces development trends for cold-rolled and cold-rolled galvanized steel sheets for body frame components, hot stamping steel sheets, and hot-rolled steel sheets for chassis components.

3.1 Properties required for automotive body structure

Figures 3–5 show the evolution of high-strength steel sheets for automotive body structural parts organized along two axes: strength and formability or deformation capability during collision. Material strength relates to vehicle collision safety, exemplified by impact absorption. Increasing strength not only enhances collision safety but also enables vehicle weight reduction. The other axis represents formability—such as stretch flangeability and bendability during press forming—or the resistance to failure during crash after the material sheets are made into parts of definitive structures.

Figures 3–5 broadly classify applicable parts into three groups based on strength and formability. The first group comprises parts requiring high strength during impact, such as bumpers (hang-on parts). Hot stamping technology is widely applied here, making it the most advanced in strength enhancement. The second group includes structural parts around the passenger compartment, like center pillars, and battery box components, where strength enhancement is progressing second only to hang-on parts. In addition to hot stamping steel sheets, cold-rolled and cold-rolled galvanized steel sheets exceeding 980 MPa have been applied. Recently, the application of 2.0 GPa grade hot stamping steel sheets to center pillars[6)] and 1470 MPa grade cold-rolled steel sheets to front pillars has also been reported[7)]. The third group consists of impact-absorbing components positioned front and rear of the passenger compartment, such as front/rear side members. These parts undergo significant deformation through axial crushing and bending during frontal or rear collisions to absorb impact energy. Therefore, they require not only strength but also sufficient deformation capacity to prevent fracture under such large deformations. The characteristics of hot stamping steel sheets and cold-rolled and cold-rolled galvanized steel sheets, as materials applied to each component group, are described below.

3.2 Hot stamping steel sheets

Cold forming of high-strength steel sheets poses several challenges, including fracture due to reduced ductility, decreased shape fixability, and increased press load. Hot stamping technology has been commercialized as one solution to address these issues. This technology involves heating the blank to approximately 900°C, corresponding to the single-phase austenitic region, followed by hot press forming. Subsequently, rapid cooling through heat extraction by the press die induces quenching, transforming the microstructure into martensite and thereby producing high strength components. Since forming is performed at elevated temperatures, the required press load is relatively low, and quenching within the die reduces residual stresses while providing excellent shape fixability.

The strength after hot stamping is determined by the quenched martensite microstructure, regardless of the initial strength prior to hot stamping. As shown in **Fig. 6**, the strength of quenched martensite increases monotonically with increasing carbon content, while the influence of other elements like Si or Mn is small. Therefore, the strength of hot stamping steel sheets is largely determined by carbon content, with 2.0 GPa grade hot stamping steel sheets requiring over 0.3 mass% carbon. With the increase in strength of hot-stamped steel sheets, the application to actual components presents challenges such as reduced toughness and deteriorated weldability associated with higher carbon content. For 1.8 GPa grade hot stamping steel sheets, these issues associated with increased carbon content are addressed by refining the prior austenite grain to ensure necessary properties like toughness and weldability.[8] Furthermore, aiming for even higher strength, countermeasures are being implemented not only from a material perspective but also from the viewpoint of utilization technology. Development is currently underway for hot stamping steel sheets exceeding a strength level of 2.0 GPa (Fig. 3).

To expand the application of components using hot stamping steel sheets, efforts are also underway to improve deformation capability during crushing. **Figure 7** shows the bending test results for a component pressed into a hat shape using hot stamping steel sheets. There is a correlation between fracture behavior in crush tests and bendability. The VDA bending angle, determined using the VDA 238-100 bending test standardized by the German Association of the Automotive Industry, is often used as an indicator of bendability. Conventional 2.0 GPa grade hot stamping steel sheets exhibit a VDA bending angle of 48°, which is about 10° lower than that of 1.5 GPa grade sheets, and cracks appeared in component bending tests. In contrast, high-bendability 2.0 GPa grade steel achieved a VDA bending angle equivalent to 1.5 GPa grade hot stamping steel sheets

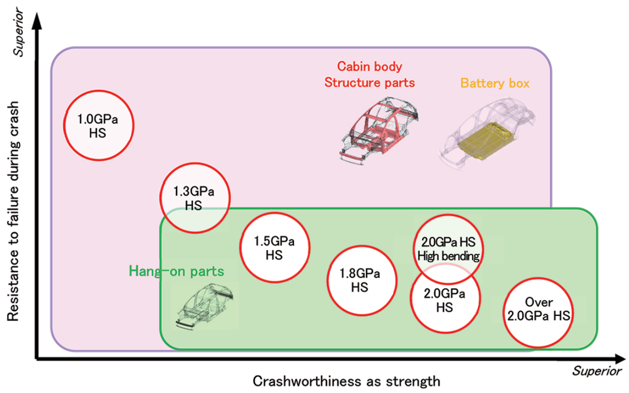

Fig. 3 Evolution of hot-stamping steel sheets for automobile body structure

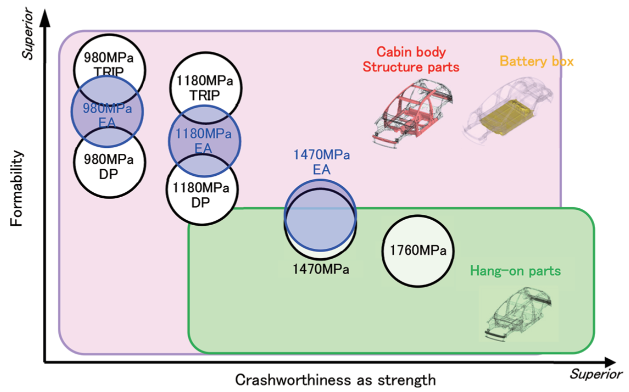

Fig. 4 Evolution of cold-formed high strength steel sheets for automobile body structure

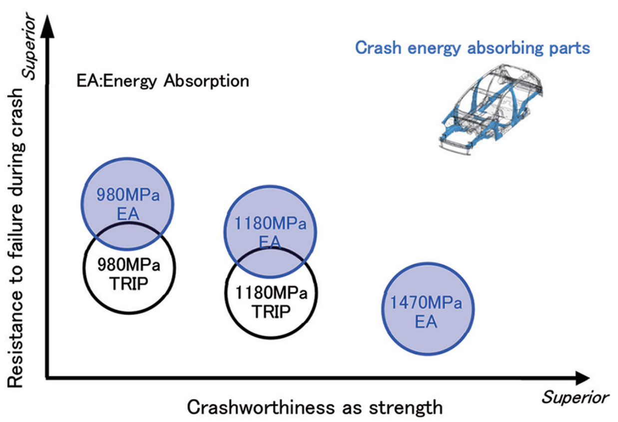

Fig. 5 Evolution of high strength steel sheets for crash energy absorbing parts

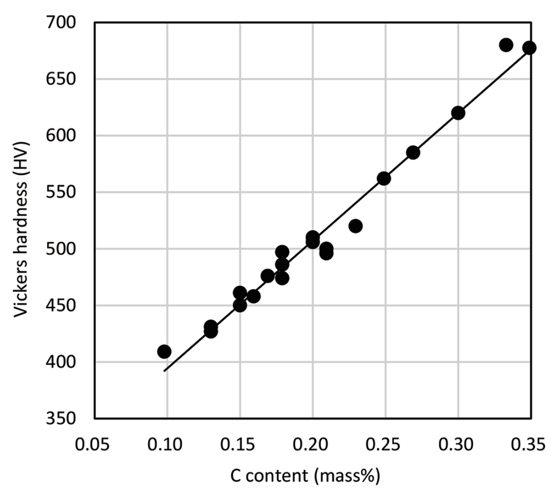

Fig. 6 Relationship between hardness in quenched martensite and C content

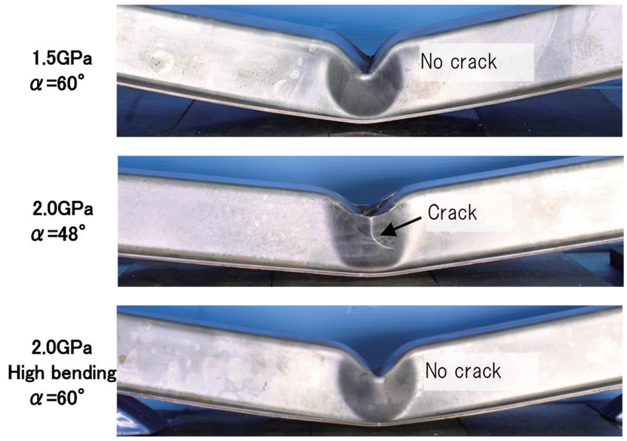

Fig. 7 Appearance after 3-point bend test in hat shape parts (1.6 mmt)

through optimized composition and process conditions, suppressing crack initiation in component bending tests. Furthermore, hot stamping steel sheets with post-stamping strength below 1.3 GPa have also been commercialized, contributing to the expansion of applicable components.[9)]

Although hot stamping involves heating in a non-oxidizing atmosphere, oxidation during transport from the heating furnace to the press cannot be prevented, resulting in the formation of an oxide scale. This oxide scale not only tends to peel off during forming and accumulate on the die, leading to increased die maintenance, but also requires removal by shot blasting if it remains on the component. To address these issues, Nippon Steel has introduced hot stamping steel sheets with alloyed hot dip galvannealing or hot dip aluminum coating. In the case of hot dip aluminum coating, Fe-Al intermetallic compounds form during heating, suppressing scale formation and enabling spot welding and chemical conversion coating. Furthermore, the formation of an aluminum passive film imparts corrosion resistance to the parts.

3.3 Cold-rolled steel sheets and cold-rolled galvanized steel sheets

Cold-rolled steel sheets and cold-rolled galvanized steel sheets, which are primarily applied to structural parts around passenger compartments, have been developed as high strength steel sheets with excellent formability, such as the previously mentioned DP steel and TRIP steel. These have already been commercialized up to the 1180 MPa grade. These steel sheets consist of multiple microstructures, including soft ferrite, hard martensite or bainite, and retained austenite that transforms into martensite during deformation. The fraction and size of each microstructure are controlled according to the required strength and formability. At strength levels of 1470 MPa and above, the microstructure becomes predominantly martensite, similar to hot stamping steel sheets. As mentioned earlier, 1470 MPa grade cold-rolled steel sheets have already been commercialized, and development is currently underway for 1760 MPa grade steel sheets (Fig. 4).

In cold-rolled steel sheets and cold-rolled galvanized steel sheets, similar to hot-stamped steel sheets, increased strength brings challenges such as reduced toughness, weldability, and resistance to hydrogen embrittlement. In addition, a specific issue for zinc-coated steel sheets is Liquid Metal Embrittlement (LME) during spot welding. LME is known as a phenomenon arising from the combination of solid and liquid metals. It occurs when highly ductile metals or alloys come into contact with specific liquid metals under load, causing a significant reduction in ductility. In recent years, LME cracking has been reported during spot welding of high strength steel sheets.[10)] The factors contributing to LME cracking in spot welding are stress/strain, liquid zinc, and material susceptibility. Cracking occurs when these factors overlap. Therefore, to suppress LME cracking in high strength steel sheets, it is crucial to implement countermeasures corresponding to each factor, and material development considering LME susceptibility is being carried out. Furthermore, there have been reports of studies utilizing finite element analysis-based spot welding simulations to evaluate the influence of clearance and welding current on stress and strain, which are the origins of LME cracking.[11, 12)]

For impact-absorbing components, such as front/rear side members, it is required not only to ensure formability but also to prevent discontinuity in deformation progression due to fracture under large deformation, thereby achieving stable crushing performance. Consequently, the application of high-strength steel sheets has been limited to the 590–780 MPa grade. To further increase the strength of these components, efforts have been made to examine the application of TRIP steels with excellent formability, as well as to develop steel sheets with superior energy absorption (EA) performance. **Figure 8** shows an example of the properties of 980 MPa grade EA steel. In terms of material characteristics, while its ductility is comparable to that of conventional DP steel, it is distinguished by improved bendability; the VDA bending angle has increased from 70° to 95°. In axial crushing tests simulating actual components, the steel demonstrates excellent energy absorption capability without fracture. The energy absorption performance of components is significantly influenced not only by material properties but also by the component shape. It has been reported that reducing the ratio of flat section width to sheet thickness (Wp/t) enhances this performance.[13)] Going forward, further weight reduction of these components is expected through optimization of component geometry and the development of 1180 MPa and 1470 MPa grade EA steel (Fig. 5).

3.4 Hot-rolled steel sheets

Hot-rolled steel sheets are primarily used for automotive wheels

	YP (MPa)	TS (MPa)	EL (%)	λ (%)	Bending angle (deg.)
EA	770	1000	14	55	95
DP	650	1000	15	25	70

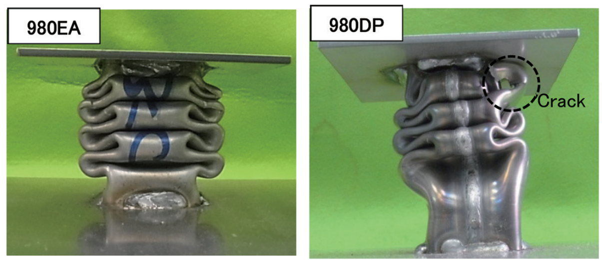

Fig. 8 Mechanical properties and axially crushed specimen of 980 MPa high strength steel for energy absorption

and suspension components. Since these parts are classified as critical safety components, steel sheets are required to provide not only strength and stiffness but also high reliability in terms of fatigue durability and corrosion resistance. Consequently, these components have traditionally lagged behind in the adoption of higher-strength materials, with 440 MPa and 590 MPa grades being mainstream. However, the application of high-strength steel sheets exceeding 780 MPa is now progressing.

Figure 9 shows the evolution of high strength hot-rolled steel sheets organized by strength and formability. Various frame components generally require lower formability compared to suspension parts, and therefore the application of high strength hot-rolled steel sheets has been advancing. For instance, 1 180 MPa grade hot-rolled steel sheets with martensitic microstructure have been adopted for underrun protection devices in medium and heavy-duty trucks.[14] Conversely, lower arms, which are representative suspension components, the part geometry requires not only ductility but also high stretch flangeability. To ensure ductility, a composite microstructure of soft ferrite and hard phases is employed. Furthermore, ferrite is strengthened through solid solution strengthening and fine precipitates, while bainite is selected as the second phase to reduce hardness differences between phases, thereby improving stretch flangeability.[15, 16] Based on these microstructure control guidelines, 780 MPa and 980 MPa grade hot-rolled steel sheets have been commercialized. These grades achieve a high-level balance between ductility and stretch flangeability while also excelling in arc weldability, bendability, and fatigue characteristics. As discussed in Chapter 2, high strength steel sheets exceeding 980 MPa are expected to deliver greater weight reduction than aluminum alloys in terms of specific strength. Therefore, development is currently underway for 1 180 MPa grade hot-rolled steel sheets with superior ductility and stretch flangeability.

Since suspension components are exposed to severe corrosion environments, hot-dip galvanized steel sheets are sometimes applied. To meet such needs, steel sheets with excellent stretch flangeability in the 590 MPa and 780 MPa grade have been developed by reducing the hardness difference between microstructural phases through integrated process control that considers the thermal history of both hot rolling and hot dip galvanizing, followed by galvanizing treatment.[17]

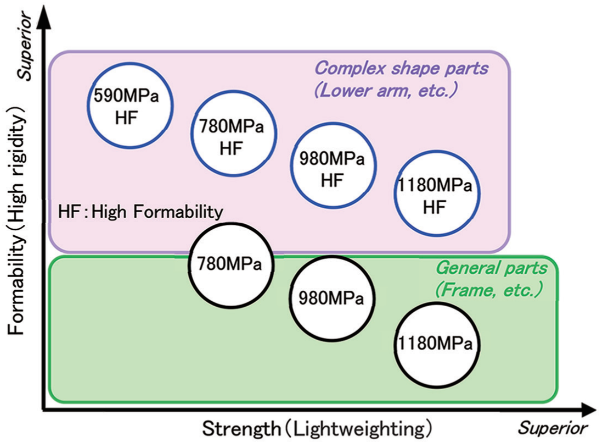

Fig. 9 Evolution of high strength hot-rolled steel sheets

4. Conclusion

This paper introduced the advanced high-strength steel sheets essential for realizing the next-generation automotive concept, NSafe™-AutoConcept ECO³. Steel materials possess high potential for strength enhancement and are an excellent material from a carbon neutrality perspective; their utilization can contribute to reducing CO_2 emissions throughout the entire lifecycle. As strength increases, technical challenges arise not only in formability but also in toughness, weldability, and resistance to hydrogen embrittlement. These challenges can be overcome through continued material development combined with advancements in processing and welding technologies, thereby contributing to the realization of a sustainable society.

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