

Steels and Their Applications for Life Satisfaction and Transportation

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1. Introduction

Steel production in Japan grew in tandem with the growth in domestic automobile production. Understandably, therefore, past development and expansion of the Japanese steel industry cannot be discussed without reference to the automotive industry of Japan.

Of all the changes in the automotive industry over the last three decades, probably the most significant was the strong demand for greater fuel efficiency. Technological developments to improve car fuel consumption were initially driven by the need to save energy triggered by the oil crisis, as typified by the Corporate Average Fuel Economy (CAFE) standards stipulated in the U.S.A. in the 1970s, and later aimed at reducing CO₂ emissions out of concern for global warming.

What spurred technological development further were tighter regulations on vehicular crashworthiness enacted in 1994; safety evaluation tests became compulsory for design approval under new regulations. In order to enhance crashworthiness, it is necessary to optimize the frame structure and other body members as well as to use stronger and heavier gauge materials, but this inevitably leads to increased weight and worse fuel efficiency. Technological development to satisfy these conflicting requirements has been one of the most important tasks of the automotive industry in recent years. The second important change was the response to environmental regulations that were originally introduced in the early 1970s, and then gradually became ever more stringent. In addition to the need to reduce CO₂ emissions for the reason mentioned above, there are regulations to control air pollution due to exhaust gas containing SO_x, NO_x and fine particles, use of hazardous chemical substances such as Pb, noise during acceleration and cruising, etc., and various control measures have been taken. Besides these two requirements, constant effort has been made to reduce costs, as is true with all manufacturing industries.

This paper outlines the technical development Nippon Steel Corporation over the last thirty years in response to the requirements of the automotive industry, focusing upon the following three aspects: (1) improving both fuel efficiency and crashworthiness; (2) improved environmental performance; and (3) reduced manufacturing costs and lead time. In addition, at the end of the article, the authors peer into the future of this field.

2. Nippon Steel's Development of Steel Products for Automotive Use

2.1 Measures to improve both fuel efficiency and crashworthiness

As stated above, the requirements for fuel efficiency and crashworthiness in vehicles conflict with each other. This section deals with the steelmakers' approaches to satisfying these conflicting requirements.

2.1.1 Evaluation of crashworthiness

While the collision characteristics of a complete car body are ultimately evaluated through crash tests using real automobiles, to clarify the effects of individual improvement measures, it is necessary to examine the deformation behavior of the structure of the whole body prescribed parts and of the individual parts. Because of cost and time limitations, evaluating all of these through experiments is unrealistic, and computer simulations using the finite element method (FEM) are widely applied. **Fig. 1** compares the calculated load-displacement relationship at an axial crush test of a square tube simulating the buckling deformation of a box-section structural member during a frontal collision with the actually experimental result of a drop weight test¹⁾.

The impact absorption capacity of a part or a structural member

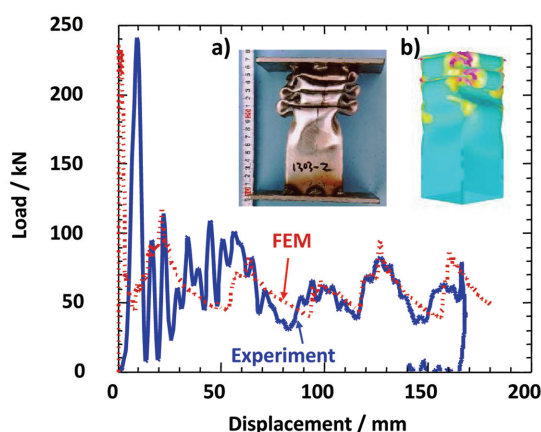


Fig. 1 Comparison between calculated and experimentally observed load-displacement relationship of an axial crush test of a square tube

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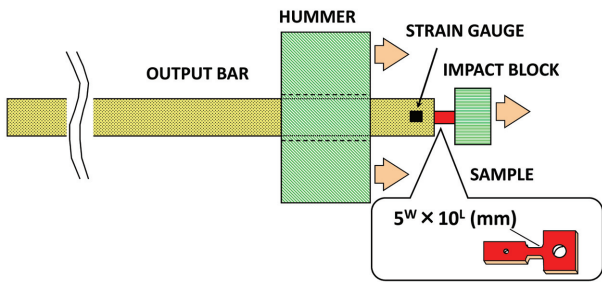


Fig. 2 Illustration of the one-bar method high speed tensile test machine

is evaluated in terms of the amount of energy absorbed while the test piece is deformed by a prescribed distance, which is obtainable from the load-displacement curve. What is most important in the evaluation using FEM is choosing constitutive equations of materials that accurately reflect the properties of the materials actually used. Different types of constitutive equations for materials have been proposed and discussed at the “Joint study meetings on the high-speed deformation behavior of high-tensile sheets for automotive use” (from April 1997 to February 2001) of the Iron and Steel Institute of Japan (for further details, see the final report of the meeting)²⁾. Equation 1 is the empirical formula proposed by Cowper and Symonds, often used for FEM calculations³⁾. Here, the values of the parameters F , ϵ_0 , D , n^* and P for individual materials are determined based on the results of tests under different strain rates.

$$\sigma \{ \epsilon, \dot{\epsilon} \} = F \cdot (\epsilon + \epsilon_0)^{n^*} \left\{ 1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/P} \right\} \quad (1)$$

Since the maximum strain rate in the case of the crush test for square tubes is as large as approximately 1,000/s in the corners, it is essential to experimentally examine the high-speed deformation behavior of steel sheets used for the frame structure members. Fig. 2 shows a high-speed tensile tester introduced for such purpose. This type of tester has proved effective in assembling a database for such information as the effects of work hardening during press forming, bake hardening after paint coating, and deformation of weld joints, etc. for different kinds of materials used for car bodies to improve the accuracy of crash simulations.

2.1.2 Compatibility of fuel efficiency and crashworthiness

Factors determining the fuel efficiency of automobiles are widely varied: besides improving engine efficiency and using new driving systems (hybrid and electric vehicles, etc.), decreasing body weight leads to better fuel efficiency under whatever conditions. In consideration of this, in addition to the increased use of aluminum alloys, plastics and other lighter materials, use of thinner steel sheets of higher tensile strength has been eagerly pursued. Because the crash performances of vehicles are determined mainly by the frame structures, the studies of the use of high-strength sheets have centered on such parts.

During a frontal or rear collision, the impact upon passengers is lowered by the plastic deformation of frame structure members, converting the impact energy into heat energy and absorbing it. In a side impact, on the other hand, since the plastically deformable space is limited, the frame structure is made as rigid as possible to minimize its deformation. In consideration of the above, different types of high-strength steel sheets are used for the structural members responsible for the impacts in different directions. What is important here is that, in order that the members work effectively, composing an entire body

in combination with each other, they are designed in complicated three-dimensional shapes, and to allow this, the steel sheets must have excellent press formability.

The press formability of steel sheets is discussed in terms of the following four aspects: deep drawability, which is determined by plastic anisotropy (r-value); stretchability, which depends on total elongation (work hardening); stretch flangeability, which is closely related to local deformability; and bendability. Because all these properties become poorer with increasing steel strength in most cases, the freedom of shape design of the body structure becomes more restricted. For this reason, higher steel strength without sacrificing press formability was earnestly sought. It is mostly the case that good r-value is incompatible with high strength, and therefore, the improvement in press formability of high-strength steel sheets has been studied especially with respect to total elongation, stretch flangeability and bendability.

While the crash energy absorbing property of frontal or rear collision by plastic deformation increases with increasing strength of the steel used, press formability improves with decreasing strength, and for this reason, steel sheets that are soft at the time of press forming and harden at the time of use, or those having strength highly dependent on strain rate, are desirable. However, the strain-rate dependence of steel strength decreases as the strength increases. It became clear that multi-phase steels, wherein soft ferrite mainly accounts for formability, demonstrate higher strain-rate dependence of the flow stress than that of conventional steels such as precipitation-hardened steels. Because the combination of soft ferrite and a hard second phase is advantageous also for improving total elongation, multi-phase steels are suitable for the structural members of complicated shapes responsible for frontal or rear collision protection.

Dual-phase steels having a microstructure of ferrite and martensite are typical steels for car body use, and others with better total elongation are low-alloy TRIP steels having mixed microstructures of ferrite, bainite and retained austenite. Fig. 3 shows the relationship between total elongation, an index of formability, and the absorbed energy in the crush test of square tubes⁴⁾. The graph shows that multi-phase steels demonstrate both good total elongation and high energy absorbing ability. The excellent energy-absorbing ability of the DP and low-alloy TRIP steels is due to the soft ferrite and excellent bake hardening properties (increase in strength resulting from pre-strain at press forming and then heating to roughly 180°C for 20 min for baking). In the case of TRIP steel, it is due also to the rapid transformation of retained austenite into martensite during high-speed deformation.

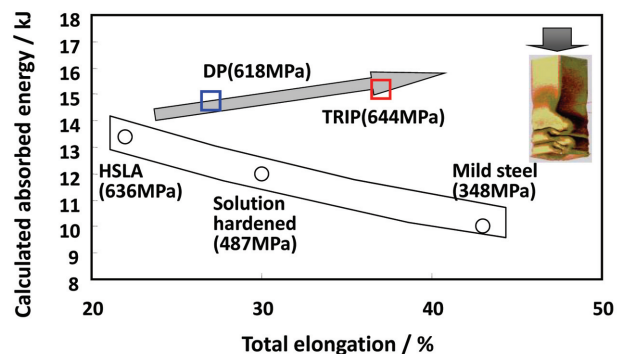


Fig. 3 Combination between total elongation and calculated absorbed energy of the crush test of a square tube

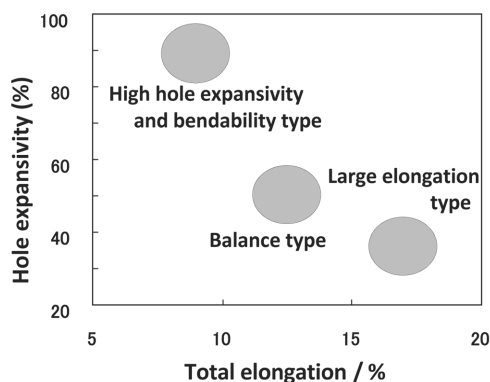


Fig. 4 Combination between elongation and hole expansivity of 980MPa grade cold rolled high strength steels

On the other hand, as high a strength as possible is desirable for the structural members responsible for side collision protection. Ultra-high-strength steel sheets of 780, 980 and 1,180 MPa class have been developed to meet this requirement. In addition to high total elongation, steel sheets for these parts must have good stretch flangeability, which determines the formability of cutting edges and bendability, etc. A homogeneous microstructure is considered to be important for enhancing stretch flangeability. Minimizing the hardness difference among the phases in multi-phase steels is effective to improve stretch flange ability, but this lowers total elongation. For this reason, Nippon Steel makes an assortment of sheet products of different combinations of total elongation and stretch flangeability (widely expressed in terms of hole expansivity) as shown in Fig. 4, and recommends different product types for parts of different shapes⁵⁾.

In addition, high corrosion resistance is indispensable for parts below the belt line. To meet this requirement, galvanized (GA) steel sheets of these high-strength steels have been used commercially⁶⁾.

For body parts requiring yet higher strength such as the structural members responsible for side collision protection and bumpers, hot stamping, whereby steel sheets are heated to the austenitic temperatures and then quenched by forming dies, is employed to increase steel strength⁷⁾; this method is able to attain a strength as high as 1,500 MPa. The alloy chemistry of the steels for hot-stamping use is designed so as to minimize the effects of uneven cooling rates at different part positions and thus to homogenize the hardness distribution after forming. Another advantage of this forming method is that, because martensitic transformation advances under constraint by the dies, residual stress is released and good shape fixability is obtained despite high strength⁸⁾. Nippon Steel has been developing methods for analyzing the forming mechanism by hot stamping⁹⁾, taking into consideration factors such as the temperature dependence of the mechanical properties, friction coefficient of the steel sheets and heat transfer between the sheets and dies.

2.1.3 Technologies for application of high-strength sheets

Advanced forming and joining technologies are essential for the use of high-strength steel sheets for structural members that bear the impact of a collision.

Efforts have been expended to improve total elongation and stretch flangeability to make up for poorer formability of higher-strength materials. However, because shape fixability depends on the deformation stress during press forming and Young's modulus.

Poor shape fixability can be classified as follows: 1) angular

change, 2) wall warping, and 3) three-dimensional deformation (twisting, edge warping). While the problems of 1) and 2) can take place in simple linear hat forming, those of 3) originate from uneven stress distribution in press-formed panels, and occur only in complicated three-dimensional forming. Spring back, an indicator of poor shape fixability during simple bending work, increases with increasing sheet strength. Wall warping, in contrast, depends on the work history of bending and unbending, and it can be decreased by applying tension during press forming work, etc.

The following methods have been proposed as measures to improve shape fixability: 1) controlling die clearance and shoulder radii so as to use reverse bending of the sheet inside the clearance; 2) the changeable bead method, wherein the blank holding force (BHF) is increased at the final stage of forming so as to apply tension to vertical walls of the work; 3) applying stress in the thickness direction by additional loading at the final stage of forming; and 4) warm forming in a temperature range where the tensile strength of the sheet is lower. Besides these, 5) methods such as crash forming and form drawing have also been proposed. Crash forming is a forming method without applying the BHF (see Fig. 5)¹⁰⁾; because this method can lower the bending deformation by die shoulders, it is possible to minimize wall warping, although wrinkles are likely to occur. Form drawing is a method whereby tension is applied to the sheet just before the lower dead center of the crash forming process to impose tension on vertical walls. Fig. 6 compares the above two proposed forming methods (crash forming and form drawing) with draw bending (a conventional drawing method) in terms of the opening after forming work into a hat section¹⁰⁾. One can understand from the graph that considerably good shape fixability is obtainable even with high-strength sheets by selecting an adequate forming method.

In order that the body members deform and absorb energy as

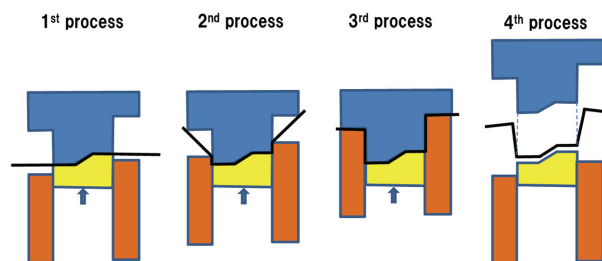


Fig. 5 Typical crash forming process of a bumper model

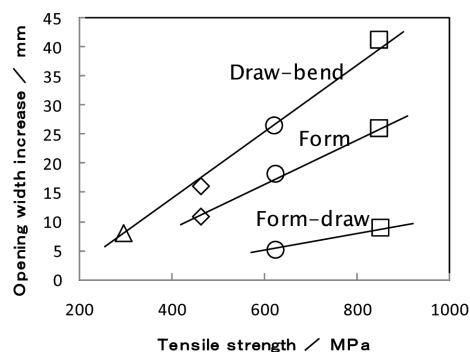


Fig. 6 Effect of press forming method on opening width of press formed bumper model

expected under collision impact, it is essential that their joints as well as the members themselves are sound. Spot welding is widely used for assembling car bodies, and besides this, laser welding, adhesion, mechanical joining, and, especially for undercarriage parts, arc welding are also used. With high-strength sheets, however, the peel strength of spot welds is feared to decrease. In this respect, it is necessary to take into consideration the higher carbon equivalents of high-strength steels as well as the effects of poor dimensional accuracy of component parts possibly leading to defective joining. (Prediction of spot weld strength under collision impact will be explained later herein.) It is possible to control the flange deformation behavior of square-section members, and improve their energy absorption ability at axial collapse by changing the joining method from spot welding to continuous laser welding¹¹⁾.

2.1.4 Further measures for lighter car bodies

In addition to activities to improve crashworthiness of car bodies, measures have been taken to reduce car body weight to enhance fuel efficiency. Some examples of weight reduction of chassis and undercarriage parts are given below.

Hot rolled steel sheets of comparatively heavy gauges are used for undercarriage parts. Both high total elongation and good stretch flangeability are essential for this application. In addition, because these critical safety parts sustain widely changing moments when driving while supporting the car weight, excellent fatigue resistance and corrosion resistance in tough environmental conditions are required.

While steel sheets of a 440-MPa class are widely used for chassis parts, Nippon Steel developed DP steel sheets of 590- and 780-MPa classes, which significantly contributed to the weight reduction of wheel discs, and hot-rolled sheets of 540 MPa or higher strength with improved stretch flangeability; these new products are expanding their applications. More recently, the company developed yet another new product for this application: namely low-carbon, hot-rolled sheets of 780-MPa class having a dual-phase matrix of ferrite and bainite wherein the differential hardness between the two phases is mitigated by solution hardening, etc. These sheets, now being used for lower arms, exhibit an excellent balance of total elongation with stretch flangeability, as well as enhanced fatigue characteristics proportionate to high strength¹²⁾.

Strengthening steel cord is important for better performance and lighter weight of tires. The strength of steel tire cord about 0.2 mm in diameter, which was about 2,800 MPa in the 1970s, increased to 4,000 MPa by around 1998. Measures such as the following were necessary for this dramatic strength increase: 1) control of pearlite after patenting so as to obtain both high strength and good work-hardening characteristics; 2) improvement in surface lubrication and shape optimization, etc. of drawing tools to increase wire drawing ratio; and 3) increase in work hardening during wire drawing to secure homogeneous deformation and prevent wire breakage during drawing. As a prerequisite for producing steel cord material, Nippon Steel established the technology to produce high-purity steels by decreasing center segregation and nonmetallic inclusions to the lowest possible level. As a result, it became possible to manufacture steel cord of 4,000-MPa class, 0.2 mm in diameter, free from delamination and offering excellent ductility; this material has been commercially used for carcass cord¹³⁾.

Valve springs are precision parts to control the intake and exhaust of engines; valves of higher strength are eagerly looked for to reduce the size and weight of engines. The principal measures to strengthen valve springs are: shape control and size reduction of nonmetallic

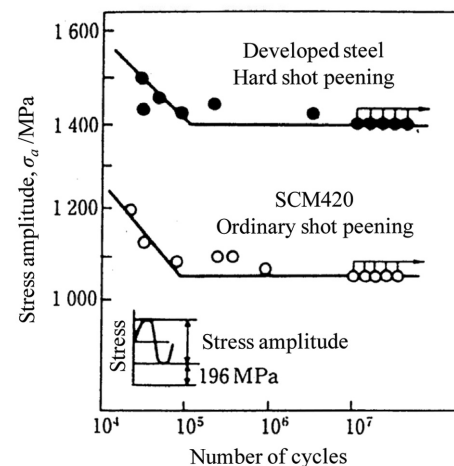


Fig. 7 Gear tooth bending fatigue strength of new high-strength gear steel

inclusions; nitriding for surface hardening; and shot peening to apply compressive residual stress. For effective nitriding, it is essential that the steel chemistry is such that internal hardness does not decrease at the nitriding temperature (anti-softening steels). Steels containing Cr, V and Mo by adequate amounts have been developed for this application¹⁴⁾. The developed steel exhibits fatigue strength higher than that of conventional high-strength valve spring steels by 35% or more¹⁵⁾. Higher hardness leads to increased sensitivity to surface defects, and therefore, improvement in ductility and other measures are necessary. Commercial production of these high-strength valve spring steels has been made possible by measures such as suppressing the formation of supercooled structure in the intermediate processes.

Gears for the transmission and other components of the drive system account for a significant part of the automobile weight. In consideration of the structural change of the transmission to new systems such as AT and CVT, the latest trend is weight reduction and downsizing by use of higher-strength materials. Two kinds of strength are required for gears: tooth-root bending fatigue strength and tooth face strength (pitting strength). Because the bending fatigue strength of carburized steel is influenced by the surface structure anomaly layer of carburizing (a layer of internal oxidation and imperfect quenching), lowering the contents of easily oxidizing elements such as Mn is effective in strengthening the steel. On the other hand, to improve pitting strength, measures to improve the resistance to temper softening such as Cr addition are effective. High-strength gear steels having excellent bending fatigue strength for tooth root and pitting strength have been developed based on the above approaches^{16, 17)}. In addition, application of compressive residual stress by shot peening is effective in enhancing tooth-root bending fatigue strength¹⁸⁾. **Fig. 7** shows the result of single-tooth bending fatigue tests of a real gear of high-strength gear steel after hard shot peening by the air nozzle method widely used recently. The bending fatigue strength of the developed steel with hard shot peening is far higher—more than 30% better—than that of conventional steel with ordinary shot peening¹⁶⁾.

2.2 Improving environmental friendliness

Examples of Nippon Steel's activities in relation to the control of exhaust gas and banning of hazardous chemicals in response to environmental regulations are presented below.

2.2.1 Responses to exhaust gas regulations

Exhaust gas regulations control air pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons, soot and particulate matter in automobile exhaust gas.

In order to mitigate atmospheric pollution, automobiles are equipped with exhaust gas purifying systems, called catalytic converters, that turn carbon monoxide and hydrocarbons into carbon dioxide and water, and NO_x into nitrogen and oxygen. The carriers for the catalyst are made of either ceramics or ferritic stainless steel foil (metal carriers). Metal carriers are characterized by low thermal shock properties and heat capacity. Nippon Steel has developed a steel grade Fe-20%Cr-5%Al (wt %) for carrier applications requiring good high-temperature and anti-oxidizing properties, and commercialized another product having improved adhesion of oxide film¹⁹⁾.

Various kinds of stainless steels are used for different parts of the exhaust systems: ferritic stainless steels excellent in high-temperature properties and corrosion resistance and austenitic stainless steels excellent in press formability are used for exhaust manifolds, which serve to suppress noise and withstand the high temperature of exhaust gases to improve combustion efficiency, front pipes and flexible tubes between the exhaust manifolds and the catalytic converters, and center pipes and main mufflers at the downstream of the converters.

2.2.2 Eliminating regulated chemicals

Use of environmentally or physically hazardous substances is controlled under laws and regulations; a typical example is lead (Pb).

The properties required for the material of automobile fuel tanks are: 1) corrosion resistance to the fuel inside; 2) corrosion resistance to salt outside; 3) solderability or weldability by resistance welding; and 4) press formability into complicated shapes. Conventionally, steel sheets coated with a Pb-Sn alloy were mainly used for the tanks because of their good balance between the above properties. As a substitute material, Nippon Steel developed hot-dip Sn-Zn-alloy-coated steel sheets equivalent to the conventional material in terms of the ease of manufacturing and superior in corrosion resistance²⁰⁾. In order that the coating exhibits both good ductility and corrosion resistance of Sn and galvanic corrosion protection of Zn by having Zn dispersed in Sn in fine particles, the Zn content of the alloy was set at 7 to 9 wt%, below the eutectic composition. The company developed another steel sheet for tank application aimed at improved cost performance: it has dual coating consisting of electrolytically deposited Ni, which is highly resistant to degraded gasoline, on hot-dip zinc coating (GI). This product proved to have substantially the same corrosion resistance as that of the sheets with Pb-Zn coating in mildly corrosive environments²⁰⁾.

Another property that steel owes to Pb is machinability. Some propose addition of Bi or S to improve machinability, but because of their poorer fatigue properties, forging performance, etc., these elements have not been considered as good substitutes for Pb. In order to solve this problem, Nippon Steel has developed a new type of free-cutting steel without Pb and excellent also in other mechanical properties by suitably controlling the shape and size of MnS particles in the steels. Here, the S content is increased to roughly 0.15 wt % from the conventional level of 0.02 wt %, and the number of MnS particles was also increased without changing their aspect ratio and size. As a result, the developed steel, which has the same tensile and fatigue properties as those of conventional steels, exhibits, for example, the same tool life and cutting force as those of conventional materials or better during deep drilling²¹⁾.

2.3 Reducing manufacturing costs

To enjoy a win-win situation with carmakers, it is important for a steelmaker to develop technologies that help carmakers improve their competitiveness in terms of manufacturing costs. Typical examples of such efforts are outlined below.

2.3.1 Advance in computer-aided engineering (CAE)

Application of FEM to the evaluation of structural performance was explained earlier herein as an example of CAE. The study of different types of plastic forming using CAE in search of the optimum structure brings about economic advantages such as shorter development periods, fewer revisions of die shapes, and skipping of work repetition in search of optimum manufacturing methods. What is important in such CAE studies is constitutive equations for different materials and how to apply the FEM to each study subject. The field application of high-strength steels mentioned earlier would have been difficult without CAE.

Predicting the occurrence of cracks and wrinkles before forming work by FEM analysis enables the optimum shapes of dies to be designed without actually making wrong ones, which means a significant decrease in the development period. The occurrence or otherwise of cracks can be judged by comparing the strain calculated by the FEM with forming limit diagrams (FLDs) showing the forming limits in different modes of deformation. In the case where the strain path changes during press forming, however, the FLD obtained under proportional loading conditions is inapplicable without modification. So as to solve the problem, Nippon Steel proposed a stress FLD method, whereby the same FLD can be used for changing strain paths²²⁾. The proposed method is applicable to failure judgment for forming work and collision simulation.

Hole expansion tests have been used conventionally to evaluate stretch flangeability, but in actual forming processes, failure often occurs under strain gradients different from that of the test. As a solution, Nippon Steel proposed the following test method: the stretch flangeability of a material is measured using test pieces having different flange corner radii and heights; the curve obtained by plotting the results is defined as the FLD for the stretch flanging work of the material; the likelihood of cracking is evaluated by comparing the material shape during actual forming work with the FLD²³⁾.

Improvement of shape fixability is essential for actual application of high-strength steel sheets, and as stated earlier, various forming methods have been developed with this in mind. If it is possible to predict spring back by FEM calculation, effective countermeasures can be taken. Regarding a sheet portion where bending and unbending are applied, it is necessary to take into consideration the Bauschinger effect and the apparent decrease of Young's modulus after stress is removed (see **Fig. 8**). In order to accurately predict the shape of such a portion after forming, it is necessary to additionally include the Lemaitre-Chaboche, the Yoshida-Uemori or the Teodosiu models in a FEM application program for general applications. Here, the Teodosiu model describes microscopic structural change of the material in terms of the evolution laws of internal state variables. The parameters of these models have been determined by using a simple shear test etc. Nippon Steel structured and proposed the method of accurate shape prediction as described above, and enabled development of countermeasures based on the prediction²⁴⁾.

An example of successful applications of CAE is that to the evaluation of collision characteristics of car bodies. Nippon Steel has analyzed the collapsing behavior of body structural parts using Equation (1) and the evaluation results of the high-speed deformation characteristics of different materials, and based on the results,

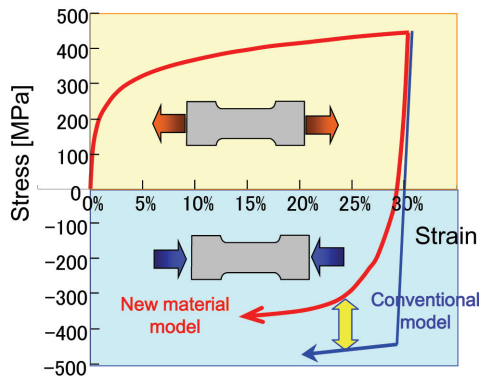


Fig. 8 Typical stress-strain curve for tensile and successive compressive deformation

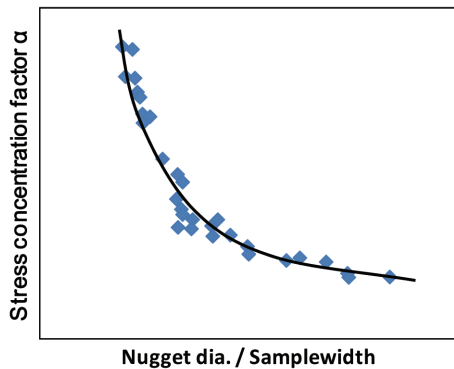


Fig. 9 Stress concentration factors as a function of nugget diameter / sample width of spot welded thin plate joints

proposed optimum arrangements and shapes of the materials for such parts. In actual collisions, failure at spot welds could influence the energy absorption behavior of the whole body. On the other hand, the failure of spot welds is influenced by a wide range of factors, such as steel quality, thickness, welding conditions, part shape and loading conditions. Nippon Steel developed a method for expressing the above nature of spot weld failure using a stress concentration factor in consideration of deformation restriction around the nugget²⁵. Fig. 9 shows the relationship between the ratio (stress concentration factor α) of the average stress at the time of failure to the deformation stress of the base metal and the ratio of the nugget diameter to the sheet width²⁵. Experiments confirmed that the relationship was independent of the steel grade, thickness, welding conditions, and test piece shape, etc. FEM calculation using this relationship has made it possible to estimate the probability of spot weld failure at a collision under given conditions. Application of this result to the collision analysis of a complete car led to improved simulation accuracy as shown in Fig. 10²⁶.

2.3.2 Technologies contributing to reduction of manufacturing costs

Besides CAE mentioned above, various technologies have been developed to decrease the manufacturing costs of automobiles. A remarkable trend in these cost-cutting measures is one-piece molding to decrease the number of forming dies and shorten joint length in each component part.

For application especially to outer side-panels and other body

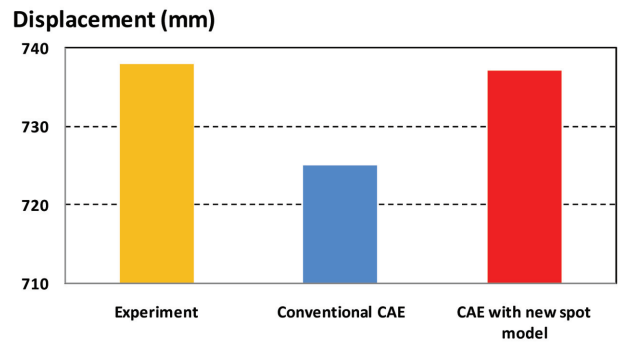


Fig. 10 Comparison between calculated and experimentally observed displacements during a complete car crush test

parts with complicated shapes, Nippon Steel developed a new sheet product with a high-purity steel having high r-value and n-value in which the crystal grains are made finer and precipitates are adequately controlled during hot rolling. However, it is often the case that required corrosion resistance or sheet thickness is different for different portions of a body component. The method of tailored blank (TB) has been developed as a solution, whereby sheets of different thicknesses for different portions of a part are welded together and then formed in one piece; laser welding, mash seam welding or plasma welding is employed for the joining. Because of the difference in thickness and steel strength, the deformation at forming work is likely to concentrate in part of the TB. In consideration of this, Nippon Steel developed a FEM analysis tool for predicting the deforming behavior including the shift of the weld line²⁷.

Besides the common cold-forming methods, Nippon Steel is proposing hydro-forming, a hydraulic method of forming steel pipes, as a solution to greatly reduce weld length by decreasing the number of component pieces. The method is suitable for obtaining complicated shapes by applying inner pressure and axial compression simultaneously to an object pipe. It enables one-piece manufacture of parts hitherto made by assembling many pieces such as engine cradles. The application of the method is expanding after its first application in Japan to the forming of the reinforcement of a center pillar.

One of the problems with galvanized sheets (GA) and other commonly used coated sheets is that the coating layers sometimes stick to forming dies, deteriorating formability. In order to resolve this kind of problem, Nippon Steel developed an inorganic lubricating film of a Mn-P system that does not adversely affect downstream processes, but is effective in securing a long service life for car bodies. This film improves the formability of material sheets and the productivity of stamping machines, reduces die adjustment work, and allows use of sheets of lower grades, significantly contributing to cost reductions in the automotive industry²⁸.

The need to reduce costs is particularly required for gears and other drive system parts too. Gears are manufactured mostly through hot forging of hot-rolled round bars of alloy steels for mechanical structural use, rough machining, tooth cutting to prescribed shapes, and then surface hardening by carburizing and quenching. The keys to cost reduction of gear manufacturing are switching to cold forging and innovation of surface hardening heat treatment.

Since machining accounts for a major part of the gear manufacturing costs, the most important issue in cost reduction is simplifying the tooth-cutting process. Cold forging is superior to hot

forging in terms of as-forged dimensional accuracy and surface finish, and thus, cold forging allows significant decrease in machining costs. When manufacturing gears by cold forging, in most cases, softening annealing is indispensable as a pretreatment. So as to skip the annealing, steels for cold-forging use have been developed^{29,30}; these steels undergo controlled rolling at low temperatures and then slow cooling in a covered cooling facility, as shown in Fig. 11, and thus are soft as rolled, and do not require the hitherto indispensable annealing. Whereas low-temperature rolling is employed to strengthen heavy plates, the same low-temperature rolling is employed to soften bars and wire-rods for cold-forging use.

Through a combination of optimum steel chemistry and TMCP, it is possible to soften steel yet further. Boron is added to the soft steel of such a chemical composition that ferrite-pearlite structure forms as rolled through TMCP while the formation of bainite is suppressed; the ferrite percentage of this steel increases by low-temperature rolling, which makes it softer yet. Boron addition is effective in securing hardenability at carburizing and increasing grain boundary strength as well as in improving fatigue strength and other strength properties of the final product³¹. Based on the above findings, Nippon Steel developed a new soft steel for cold-forged gears that allows elimination of spheroidized annealing³². As shown in Fig. 12, the as-rolled cold deformation resistance of the developed steel is the same as or lower than that of a conventional steel after

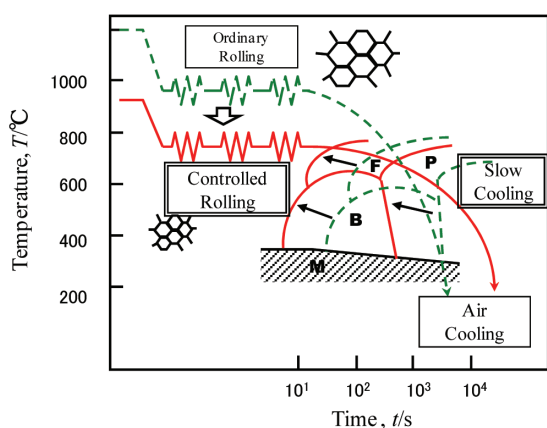


Fig. 11 Illustrative mechanism of softening of alloy steels using controlled rolling and controlled cooling techniques

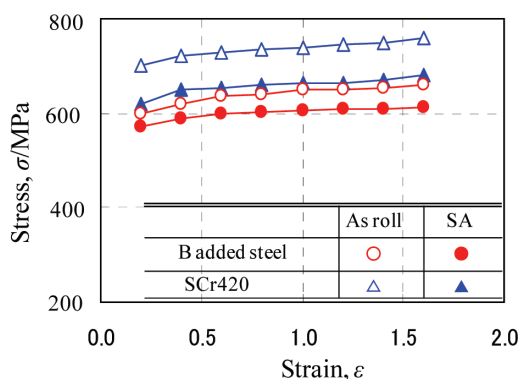


Fig. 12 Stress-strain relationships for as rolled and spheroidization annealed SCr420 type developed steel

spheroidized annealing (SA steel).

Additionally, for such cold forging applications that the ductility of steel governs the occurrence of cracks, Nippon Steel developed another type of steel with improved ductility through the combination of the TMCP and post treatment by spheroidized annealing³³.

A problem with steel for cold-forging use is that coarse grains form readily when cold-forged materials are carburized. This is because the initial austenite grains that have formed during the heating to carburize cold-forged materials become finer, increasing the driving force for the growth of abnormal grains. As a countermeasure, Nippon Steel developed a steel for cold forging wherein coarse grains are prevented from forming by having fine precipitates of AlN, Nb(CN), TiC, etc. dispersed in great quantities as pinning particles³⁴.

Another approach to cost reduction for gear manufacturing is innovation of surface hardening treatment. Gear surfaces are hardened mostly by carburizing and quenching. Aiming for higher productivity through in-line processing, the application of induction heating is being studied. With induction heating, it is possible to heat the gear surface selectively and at a very high rate, and as a result, only the surface layer is hardened, and very high compressive residual stress is applied there. Thanks to this, it is possible to obtain high bending fatigue strength even with medium carbon steels containing roughly 0.53% C. On the other hand, homogeneous solution treatment at very high heating rates is indispensable for surface hardening by induction heating³⁵, and in view of this, Nippon Steel is developing a new type of steel suitable for the treatment³⁶.

2.3.3 Joining technology for high-strength steel sheets

As stated earlier, the peel strength of spot welds tends to lower as the steel sheet strength increases. Because the strength of spot welds has a significant effect on the collision energy-absorbing ability of car bodies, it is necessary to develop sheet joining methods with exceptional peel strength. A study of cross-tension tests of spot welds applying elasto-plastic fracture mechanics indicated that the decrease in peel strength of spot welds with increasing sheet strength was due to low weld toughness³⁷. In consideration of this, Nippon Steel developed a spot-welding method whereby post heat is applied after the welding, as shown in Fig. 13³⁸. The reason for post heat being effective in improving peel strength is probably that segregation of impurity elements in the solidification microstructure of weld joints is mitigated, and consequently, toughness is improved. Whereas by

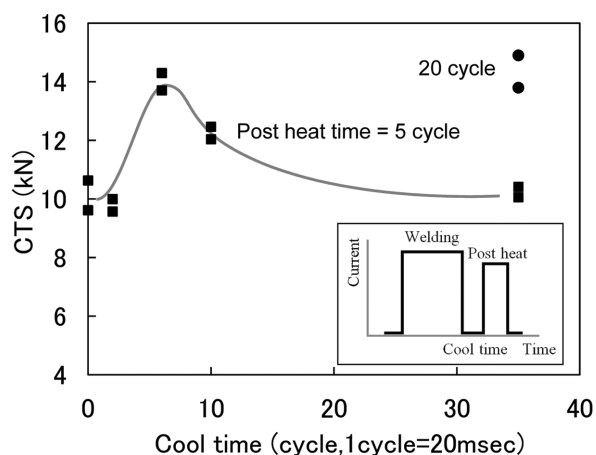


Fig. 13 Improvement of cross tension strength in spot welded joint of TS1,470 MPa grade steel sheet in 2.0mm thickness by post heating

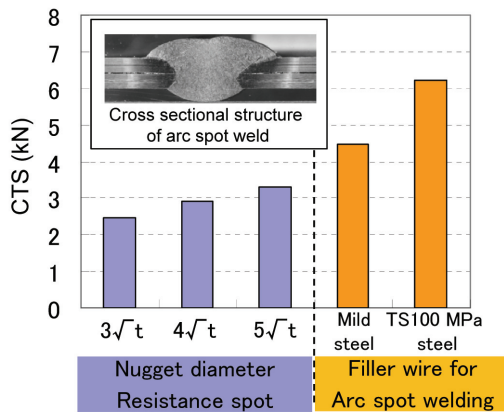


Fig. 14 Comparison of cross tension strength between spot welded joints and arc-spot welded joints in TS 1,470 MPa steel sheet of 1.0 thickness (“Mild steel” means welding consumable for mild steel and “TS 1,000 MPa steel” means welding consumable for TS 1,000 MPa steel in arc-spot welding.)

spot welding the chemical composition of weld metal is the same as that of the base metal, the chemical composition of weld metal can be made different from that of the base metal in arc welding, where filler metal is provided from outside. It became clear that, as seen in **Fig. 14**, arc spot welding can realize a peel strength roughly twice that of common spot welding by selecting an adequate filler metal³⁹⁾. On the other hand, when high-strength sheets are used and a reinforcement is eliminated, there will be three-sheet welds of a thin sheet of an outer panel and two thick high-strength sheets (a reinforcement and an inner panel). It will be difficult by spot welding to form a nugget between the thin outer panel and the high-strength reinforcement because the sheet surfaces are cooled through heat conduction to the water-cooled electrodes. For such cases of three-sheet welding of large thickness ratios, Nippon Steel proposed a hybrid welding method whereby the two thick sheets are joined by spot welding and the thin outer panel is joined by remote laser welding⁴⁰⁾. In welding, the steel material is melted, and therefore the microstructures of the sheets inevitably change, however small the heat input may be. In this regard, the company also studied the possibility of joining high-strength steel sheets mechanically using blind rivets, and confirmed that peel strength increased with increasing sheet strength⁴¹⁾.

3. New Trends and Future Prospects

3.1 Increase of hybrid and electric vehicles

Obviously, the future trend of the automotive industry should be discussed with a focus on the change in drive system. In addition to conventional drive systems using internal combustion engines, one alternative using it in combination with an electric motor, and another using an electric motor only are likely to become popular. With respect to internal combustion engines, diesel engines, already widely used in Europe, will become a common alternative to gasoline engines in Japan too. Another type of internal combustion engine used in some countries burns gasoline mixed with alcohol to reduce CO₂ emissions. Whether the power for the electric motor is stored in a battery or is generated using hydrogen is fully established yet, but use of electric motors is becoming increasingly important out of consideration for

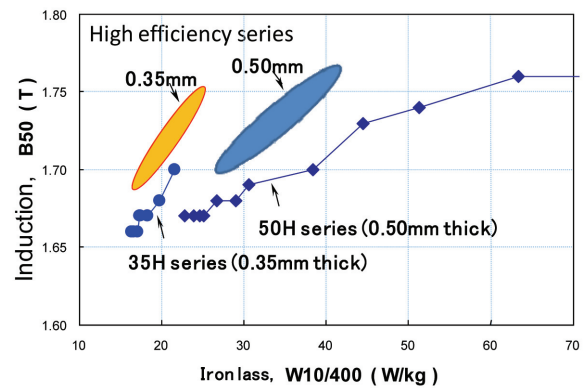


Fig. 15 Typical magnetic properties of high efficiency electromagnetic steels for motors and generators

reducing CO₂ emissions and consumption of fossil fuels. In this regard, electrical steel sheets for motors, and steel materials for batteries and related components are expected to contribute to reduced consumption of fossil fuels.

Typical properties required of electrical steel sheets for motors in electric vehicles (EVs) are a high magnetic flux density to enable high motor torque at low revs from start through slow speeds, and low core loss at high revs for cruising at high speed. In response to the increase in hybrid vehicles (HVs) and EVs, Nippon Steel has developed and marketed highly functional electrical steel sheets for motors as shown in **Fig. 15**⁴²⁾. Higher strength is now required of electrical steel sheets to allow higher revs, and to meet this requirement, the company has developed electrical steel sheets with higher yield points having core loss properties comparable to those of conventional products⁴²⁾.

The core loss of a real electric motor depends not only on the core loss of electrical steel sheets, but also on the effects of the fluctuation in magnetic flux and harmonics as well as stress and strain in the steel sheets resulting from the blanking and caulking in the motor manufacturing processes. In order to measure the adverse effects of these factors quantitatively and take measures to minimize them, Nippon Steel developed various methods for measuring such factors and numerical calculations of electromagnetic fields to contribute to better understanding of the effects of the stress and strain and to optimize motor design⁴²⁾.

3.2 Future prospects

The market shares of hybrid vehicles (HVs) and electric vehicles (EVs) will certainly increase, but automobiles powered by internal combustion engines, burning different kinds of fuel, will certainly remain the mainstream of the automotive industry for some time yet. As is widely discussed, the cost of batteries and construction of the infrastructure system to supply electric power to automobiles will no doubt have a significant influence on the popularization of HVs and EVs.

On the other hand, while an intelligent transport system is earnestly discussed, it will still be quite a time until such an ideal system expands coverage outside urban areas. Then, whichever the future drive power of automobiles may be, improvement in both energy saving (power efficiency) and crashworthiness will be an everlasting target for those involved in the automotive industry. It follows therefore that, in order to meet the unchanged requirements

for lighter cars and better crashworthiness while improving economic efficiency, stronger steels will be required of the steel industry and optimum structural design of the automotive industry. Thus, we have to further sharpen our expertise to develop high-strength steels excellent in press formability and functionality and the methods of their applications.

The steel industry has supplied the automotive industry with high-strength thin steel sheets offering excellent elongation, stretch flangeability and weldability, thin steel sheets and bars of medium- and high-carbon steels with excellent cold-forging properties, new working methods for such high-strength steels, technologies to enhance the performance of weld joints, corrosion protection measures for portions around weld joints, and countermeasures against hydrogen embrittlement of ultra-high-strength steels, etc. In addition, it is necessary to develop new forming, joining and corrosion protection technologies in consideration of the optimum multi-material combination with aluminum, titanium, plastics, etc. for automobiles. Such development of new materials and applications will serve as support for securing and enhancing our competitiveness in the now borderless international market of automotive materials, as well as for strengthening the manufacturing power of Japan's basic industries.

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