NIPPON STEEL TECHNICAL REPORT No. 88 July 2003

UDC 699 . 14 . 018. 295 - 415 : 629 . 11 . 011

Development of High Strength Steels for Automobiles

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Abstract

High strength steels have been intensively applied to autobodies to improve crashworthiness without increasing the body weight under a strong pressure of the requirements for fuel consumption, energy saving and crashworthiness. One of the critical problems of the usage of high strength steels for autobodies is a deterioration of press formabililty with increasing the strength. Different types of high strength steels have been developed at Nippon Steel Corporation to respond to the requirements of auto-companies. The features of these high strength steels with different kind of press formability will be summarized here with their performances of crash energy absorption property, fatigue strength and so on.

1. Introduction

Automobiles play an important role in part of our daily life. This makes it necessary to incessantly try to reduce their production cost in line with the innovation of production technology. At the same time, measures are being taken toward the reduction of fuel cost and the improvement of safety so that eagerly-pursued harmony with the social and natural environment can be established. It is safe to say that thin steel sheets for automobiles have made progress in responding to the market needs. In recent years, it has become one of the most important tasks for automobiles to make the reduction in weight of auto bodies compatible with the improvement of crashworthiness, particularly with the aim of reducing CO_2 gas emissions by improving fuel consumption. The applications of high strength steel sheets are expanding as one of the means of satisfying those demands conflicting with each other. Steel sheets for automobile components are required to have different strength characteristics from part to part (**Table 1**). Except for the cases in which the effects of characteristic improvement due to an increase in steel sheet strength cannot be expected, including rigidity, corrosion, and fatigue strength at welded parts, enhancing the strength of steel sheets is considered to contribute to thinning, that is, weight reduction, of steel sheets.

According to the research in 1998 by the High Strength Steel Sheet Working Group, a substructure of the joint research society of Iron and Steel Institute of Japan and Society of Automotive Engineers of JAPAN, in 2002, the 4th year, the following classes of steel strength were expected to be the average strength levels[1)]:

Table 1 Required properties and main controlling factors of various vehicle parts

Part		Required properties				
		Panel rigidity	Dent resistance	Member rigidity	Fatigue strength	Crash strength
Outer panels	Door outer, etc.	◎	○			
Inner panels	Floor, etc.	◎		○	○	○
Structural parts	Front rail, rear pillar, etc.			◎	○	○
	Front side member, side sill, etc.			◎	○	◎
	Door reinforcement, etc.			○	○	◎
Underbody parts	Suspension arm, disc wheel, etc.			◎	◎	
Main controlling factors apart from thickness of steels		Young's modulus	Yield strength	Young's modulus	Tensile strength	Tensile strength

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Exposed panels : 340 MPa class
Structural members including pillars and other members
: 440-550 MPa class
Reinforcement : Ultrahigh strength steel partly over 1,000 MPa class
Chassis : 490-590 MPa class

In this report, with auto parts classified into exposed panel, structural, reinforcement, and chassis parts, the characteristics of high strength steel, expected to be applied to respective parts, are mainly described.

2. Press formability of high strength steel sheets for automobiles

Thin steel sheets are required to have not only the strength characteristics to be applied to respective components, but also the press formability into various complicated shapes. Steel sheets for automobiles are generally press formed into final components, and their press formability can be classified into four modes as **Fig. 1** shows[2]. Steel sheets are press formed between the punch and the die after blanking to appropriate sizes in the following modes:

1) Deep-drawing, also called shrink flanging, by which a large formed height can be secured by pouring the material effectively in between the punch and the die as represented by cup forming
2) Stretching in which the material is stretched in a manner to inflate a balloon by thinning the material
3) Stretch flanging in which the cutting edge of materials experiences a large tensile deformation in a manner to expansion of pieced hole
4) Bending

All the parts are actually formed by a combination of those modes. Since the required properties of steel sheet ,which are obtained by mechanical tests, depend on the press forming mode, Nippon Steel has so far developed different types of steel sheets for each press forming mode to be applied.

In deep-drawing , since the flange part is required to reduce its volume between tools, shrinking is essential for this part. Such deformation characteristics are represented, for example, by a limiting drawing ratio (LDR), which is the ratio between the maximum disk radius and the radius of a cylindrical cup to which the disc can be drawn successfully. LDRis known to be closely interrelated with the plastic anisotropy (r-value) of a steel sheet. Those characteristics play an important role, particularly in the inner and outer panels of auto bodies, and various methods such as reducing the carbon content in a steel sheet and fixing carbon and nitrogen atoms by Ti and Nb, are adopted to improve r-value. It is not easy, however, to enhance r-value in high strength steels more than 500 MPa in tensile strength.

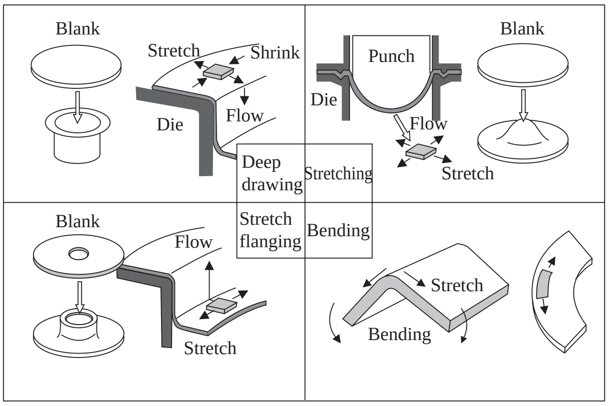

Fig. 1 Categories of deformation mode in press forming of sheet steels

Stretching aims at securing a domed height while reducing sheet thickness without allowing the influx of material, and is represented by limiting dome height(LDH). LDH is known to be closely interrelated with the ductility, particularly with the uniform elongation of steel. Since it is generally impossible to secure large r-value in high strength steel sheets as described above, stretching, that is, ductility, is the most common index of press formability of high strength steels. Since the ductility is known to decrease with increasing the strength, stretchability generally decreases with increasing the strength of steels.

Stretch flangeability indicates the formability of the edges, particularly cutting edges. It is typically evaluated by the hole expanding test in which a pierced hole is expanded with a conical punch. A ratio of diameters of the hole before (do) and after (d) hole expansion test is used as an index (Hole extension ratio λ (%) = 100 × (d – do)/do), and is known to correspond well to the local ductility. The ratio is known to be improved by increasing r-value. However, since the r-value of high strength steels is generally less than 1.0, other controlling factors become important. Although stretch flangeability is also known to decrease with increasing the strength, the effect of microscale uniformity is noticeable. The more uniform the microstructure, the better stretch flangeability can be obtained. It is, therefore, important to reduce the amount of hard carbide and oxide particles, and to disperse them finely. Stretch flangeability is also known to be influenced strongly by microstructure.

Bending poses a problem, particularly at very high strength levels. Bendability can also be construed similar to stretch flangeability as a flacture due to a large local deformation, and can be put in order, for example, by the scatter of hardness (corresponding to the distribution of hard and soft phases of microstructure) for 980MPa-class steel. Accordingly, the improvement of bendability can be achieved by the same concept as in the improvement of stretch flangeability.

3. High strength steel sheets for automobiles and their characteristics

As described above, due to the differences not only in the characteristics required for the parts of an automobile, but also in the level of strength mainly applied, parts are classified into panels, structural parts, reinforcements, and chassis, and high strength sheets suited to the respective parts are discussed.

3.1 High strength steel sheets for panels

Since the panels are generally expected to be formed by deep drawing, IF (Interstitial Free) steel is widely used, in which, solute C and N atoms are fixed by Ti and Nb as precipitates in ultra-low carbon steels. Extremely formable steel sheet with average value r = 2.5 and work hardening coefficient n = 0.27 has been developed by a combination of grain refinement of ferrite through high reduction hot rolling at low temperatures and accelerated cooling immediately after hot rolling, high reduction cold rolling, and high-temperature annealing[3]. This steel sheet is considered to contribute to the reduction in production cost by saving metal die cost and the omission of joining processes through the integrated forming of complicated parts.

3.1.1 High BH steel sheets

Exposed panels are required not only to have panel rigidity to be determined by the Young's modulus, thickness, and geometric configuration of the parts, but also to be resistant to denting (dent resistance) when they are pushed by fingers or struck by small stones. Although it is effective to increase yield strength for the improve-

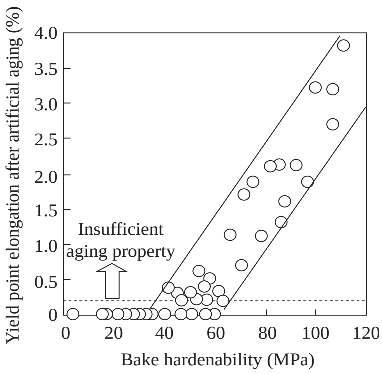

Fig. 2 Relation between bake hardenability and aging property

ment of the dent resistance, it is necessary to maintain yield strength below 240MPa so that high surface quality can be secured against surface distortion in press forming. To satisfy those conflicting requirements, baking-hardenable (BH) steel sheets with low strength (low yield strength) at press forming stage and with high yield strength in use, have been developed and commercialized.

The BH effect stands for a phenomenon in which C and N atoms remaining in solid solution diffuse to dislocations introduced by press forming during baking after coating (corresponding to heat treatment at 170 °C for 20 minutes) and pin the dislocations resulting in an increase in yield strength. Accordingly the higher the amount of solute C and N, the higher the bale hardenability can be obtained. However, solute C and N atoms remaining in a steel sheet can cause an aging, resulting in a surface defect called stretcher-strain due to yield point elongation. Since stretcher-strain is not practically observed when the yield point elongation after one-hour of accelerated aging heat treatment at 100 °C is less than 0.2%[4], the practical amount of BH is around 30 - 50 MPa (**Fig. 2**).

There are two methods by which BH steel sheets are manufactured using ultra-low carbon steel as follows: one is when C and N are added more than the stoichiometry of Ti and Nb, and the other, when the addition of C and N is less than the stoichiometry. In the former case, it is known that the presence of the solute C and N atoms can prevent the development of desirable crystal texture good for r-value. On the other hand, in latter case it is necessary to allow a proper amount of C atoms in solid solution in the final product through dissolving of carbide particles during high-temperature annealing. Nippon Steel has commercialized high-BH steel sheets at 270 and 340 MPa levels employing a method to control the amount of solute C and N with the addition of appropriate amount of Ti and Nb adjusted to the alloy chemistry without adopting costly disadvantageous high temperature annealing[5].

3.1.2 High strength steel sheets with excellent deep-drawability

Application of higher strength steels to outer panels has already been under consideration by some automobile manufacturers. A 440 MPa class high strength steel sheet with excellent press formability with a total elongation of 38.3%, n-value of 0.24, and r-value of 1.95 was developed by solid solution hardening Nb-Ti bearing ultra-low carbon steels with P, Mn, and Si[6]. As a special example, a high-r-value high-strength steel sheet has also been developed at a level of 590 MPa with r-value of 1.9 by strengthening Ti bearing IF steel with high r-value after cold rolling and annealing, with Cu precipitation through successive heat treatment at around 600°C[7].

3.2 High strength steels for structural parts and reinforcements

Many of the structural parts are used to protect passengers in the case of a car crash, and are expected to be strengthened most urgently in line with the intensifying safety regulations and the growing demand for fuel consumption. These parts secure a survival space for passengers on a frontal collision not only by absorbing energy through the buckling and bending of the structural parts, such as a front-side member, thus to reduce physical injury to passengers, but also by preventing the engine and its peripherals from breaking into the cabin space. On the other hand, in the case of side collision, the plastic deformation of the structural parts reduces passenger survival space. Therefore, the structure is designed as rigid as possible to minimize thrusts into the cabin.

For example, in the case of a part, such as a front-side member, which experiences an axial crash at a collision, the deformation speed at corners is known to reach to about 1000/s of strain rate, which is one million times faster than the deformation speed in the normal tensile test[8]. Hereinafter, the normal tensile test is called “static”, and the other at 1000/s, “dynamic”. The capacity of the energy absorption of a component at a collision event can be obtained either by FEM analysis with the proper constitutive equation in which strain rate dependence is taken into account, or by the direct meas-urement using a weight drop tester. It has been shown by the FEM analysis that the absorbed energy during an axial crush of square tubes shows linear relationship with the dynamic flow stress at strains below about 10%[8]. In the case of a part such as a center pillar, it can be said that the higher the strength of the materials the more effective to preserve the survival space of passengers.

It is, therefore, essential to make accurate measurement of dynamic stresses in order to assess the deformation behavior and absorbed energy of components during crash. We then installed One-Bar method high-speed tensile test machine at Nippon Steel[8]. The load during a dynamic tensile test is measured as the elastic deformation of the 5 m long output bar. In the high speed mechanical test, the load measurement is designed to complete before a shock wave transmits into this output bar and returns to the position of the strain gage for load detection, enabling to measure a smooth stress-strain curve not influenced by the shock wave without filtering. Furthermore, a peak, induced by the impact test method, occurring at the initial part of the stress-strain curve can be eliminated by controlling the local oscillation at the end of the output bar thus to render highly precise measurement possible.

3.2.1 Highly ductile multi-phase steel sheets for crashworthiness

Structural components and their reinforcements, expected to absorb energy on collision, are required to have good formability enable to press-form into complicated shapes. Stretchability, which well corresponds to elongation, plays an important role for high strength steels in press forming since high r-values cannot be expected in high strength steels. It is well established that elongation generally decreases with increasing the strength of steel sheets. It is known, however, that DP (Dual-Phase: ferrite + martensite microstructure) steel with soft ferrite as a major phase, or low alloy TRIP (Transformation Induced Plasticity: ferrite + bainite + residual austenite) type multi-phase steel (designated as low alloy TRIP steel hereafter) show larger elongations than the precipitation, solid solution and transformation microstructure hardened steel sheets with the same strength[9].

Galvanealed DP steel sheets with a larger elongation than the conventional steels have also been developed and commercialized[10]. TRIP steels were first reported by Zacky et al[11]. in highly alloyed systems . The low alloy TRIP steels are, however, the steels with retained austenite which is stabilized with inexpensive carbon in steels. The low alloy TRIP steels contain several to some 20% of residual austenite. As **Fig. 3** shows, austenite transforms to hard (high carbon) martensite as plastic deformation proceeds. As a result, the steels exhibit an extremely high work hardenability throughout a wide rage of strain, and thus show a good stretchability[12] (**Fig. 4**).

It is worth to note that the low alloy TRIP steels show an excellent deep drawability as well as stretchability. This good deep drawability can be understood as follows. Since the martensite transformation is influenced by the deformation mode, the amount of transformed martensite obtained during the deep drawing at the flange area, at which the deformation mode is shrink flanging, is smaller than that at the wall area under plane strain mode (**Fig.5**). This difference in transformation from austenite to martensite makes the wall area stronger than flange area. As a result, the flange area can be pulled into the die very smoothly without any breakage at the wall.

Although the difference between dynamic and static stresses (dynamic-static difference) decreases with increasing the strength of steels, it has been recognized that the dynamic-static difference is influenced by the way of strengthening. As is clear from **Fig. 6**, DP and low alloy TRIP steels with ferrite as a major phase show a higher energy absorbing property than the conventional high strength steels, particularly after pre-deformation and baking treatment[8]. One of the reasons is that those multi-phase steel sheets show relatively large BH effects. An enhancement of the transformation from retained austenite to martensite especially at small strains by increasing the strain rate is also another reason for the higher dynamic-static difference. The fact that ferrite as a major phase is softer than that in the steel with solid solution or precipitation strengthened steels, is also one of the reasons of the high strain rate dependence. Calculated crash ab-

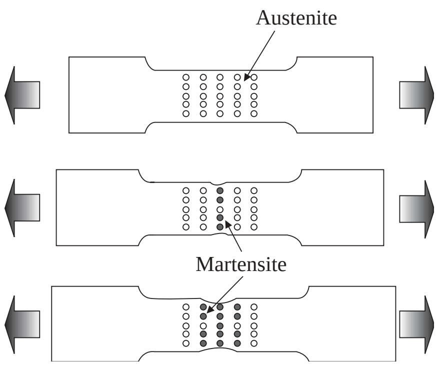

Fig. 3 Mechanism of the enhancement of ductility due to TRIP efffect

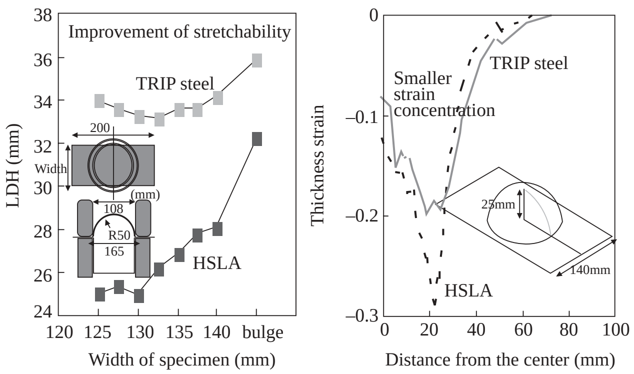

Fig. 4 Enhancement of stretchability due to TRIP effect

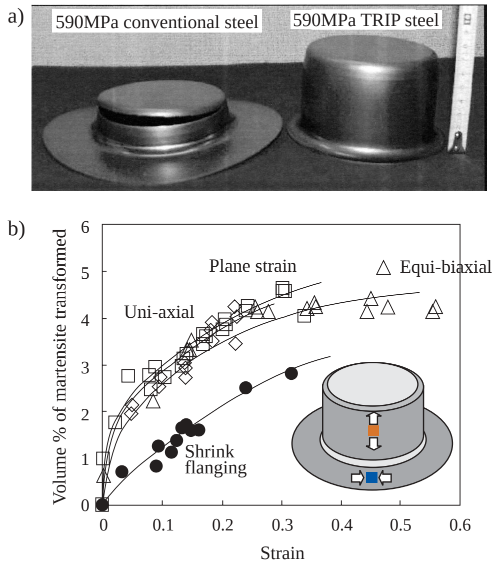

Fig. 5 Deep drawability of low alloy TRIP steel

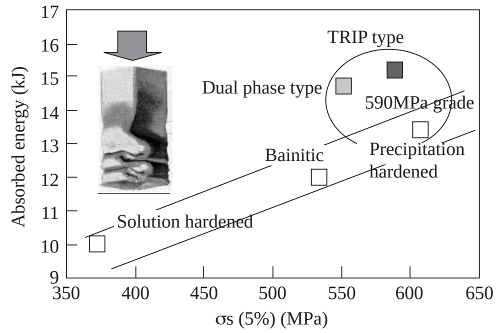

Fig. 6 Effect of strengthening method on the relation between static strength and calculated absorbed energy

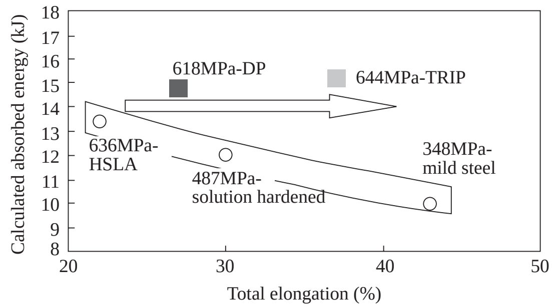

Fig. 7 Relation between total elongation and calculated absorbed energy during axial crush of a square tube

sorbed energy of a square tube is platted against total elongation in **Fig. 7**[13]. Energy absorbing capacity increases with the strength of steels. However, the elongation of steel sheets decreases with increasing the strength of steels, making it difficult to press-form into complicated shapes. However, DP and TRIP steels can be considered as desirable high strength steels for crashworthy parts since they have not only a high energy absorbing capacity but also a large elongation.

3.2.2 Ultra-high strength steel sheets

Ultra-high strength steel sheets with the tensile strength of 980

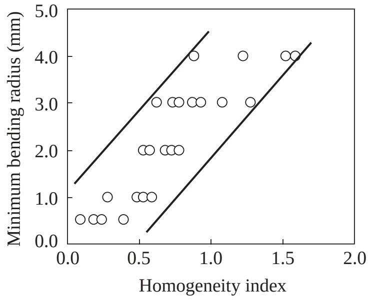

Fig. 8 Relation between minimum bending radius and homogeneity index of microstructure of ultrahigh strength steel sheets

MPa or more have been applied to bumper reinforcement and to components for complying with side crash. Not only elongation but also bendability and stretch flangeability are important factors of formability for these ultra-high strength steels. It is effective to adopt mixed microstructure to improve elongation as described above. Cold-rolled DP steels up to 1,180 MPa in tensile strength have been developed and commercialized. However, the mixed microstructure of a soft phase and a hard phase is considered to be disadvantageous for the improvement of bendability. Homogeneity of microstructure, which can be characterized by a standard deviation of the micro-hardness, is more important to improve the bendability as shown in **Fig. 8**[14]. Furthermore, as reported in this issue, 980 MPa grade high strength steels with various types of formability requested for different application have also been developed and commercialized.

3.3 High strength steel sheets for chassis

Fatigue strength and corrosion resistance as well as rigidity are strongly required for chassis as described above. Hot rolled steels are widely used for chassis because relatively thick gauges are required.

3.3.1 Highly ductile hot-rolled steel sheets

The most ductile steel among hot rolled high strength steel sheets is low alloy TRIP steel (retained austenite steel). When steel sheets are used as hot-rolled, they are cooled after finishing hot rolling and coiled at about 400 °C allowing bainite transformation proceed to stabilize austenite. The elongation of low alloy TRIP steel is closely interrelated with the volume fraction of retained austenite. However, when steel sheets are used as hot-rolled, it is effective to enlarge the ratio between the volume fraction of austenite and ferrite grain size by optimizing the hot rolling conditions and successive cooling conditions[15]. Hot-rolled TRIP steel is not only highly ductile but also excellent in crash energy absorbing property as described above. In addition, because of its good fatigue resistance, it can be expected to find various applications. Since low alloy TRIP steels have mixed microstructure of hard and soft phases, they are generally considered to be inferior in stretch flangeability as in expanding pierced hole. As reported in this issue, low alloy TRIP steels with high stretch flangeability have also been developed which have overcome the above-described defects by controlling the chemical composition and microstructure of the steel.

3.3.2 High burring hot-rolled steel sheets

Stretch flanging is often applied to under-body parts in which shared edges are stretched. As described above, this stretch flangeability is evaluated by the hole expansion test. Since the higher the homogeneity of microstructure, the better the stretch flangeability can be obtained, high strength steel sheets with an enhanced stretch flangeability (high burring hot-rolled steel sheets) have been developed by controlling the microstructure to ferrite + bainite or bainite single phase. It is also worth noting that refinement of cementite particles, inevitably present in conventional steels, is effective to improve stretch flangeability. High burring steels of around up to 590 MPa in tensile strength have been developed in which cementite particles are refined through alloy addition such as Si which has very low or no solubility in cementite resulting in a retardation of the growth of cementite particles[16]. Furthermore, as reported in this issue, 780 MPa class low carbon high strength steel sheets with high hole expansivity have also been developed and commercialized.

3.3.3 High strength steel sheets with excellent weldability

When arc welding is used to join steel sheets, attention should be given to the fact that the strength properties could be deteriorated by the softening at heat affected zone (HAZ) of the welding. Anti HAZ softening steels have been developed by adding Nb and Mo which interact with dislocations preventing their annihilation and accelerating the formation of (Nb, Mo) C complex precipitates on the dislocations[17].

3.3.4 High fatigue strength steel sheets

Under body structural parts including wheel discs and suspension arms, are required to have high fatigue strength. It is common to encounter fatigue problems at welded joints, shared edges, and stress concentrated areas depending on the geometry. Since the fatigue life is considered to be determined rather by the initiation of fatigue cracks than the propagation of them in the case of thin steel sheets, it is effective to increase the fatigue strength of bulk steels.

It is well established that DP steels with mixed microstructures of Si solid solution hardened ferrite and finely dispersed hard martensite exhibit high fatigue strength[18]. Low-cycle fatigue experiments tells us that Si solid solution hardened hot-rolled DP steels show high and steady cyclic stress due to the fact that the dislocation cell structure produced at a very early stage of the fatigue test is stable. This high cyclic resistance seems to prevent the initiation of fatigue cracks. DP steels with excellent combination of ductility and fatigue strength have been developed by decreasing the bulky bainite microstructure and diminishing an abnormal grain structure of a mixture of fine and coarse grains near the surface of the sheets[19]. DP steels with the strength up to 780 MPa have been developed and commercialized now. Fatigue strength is known to relate closely with cyclic yield stress (**Fig. 9**). Low alloy TRIP steels also show higher fatigue strength as DP steels than other high strength steels[19]. The high fatigue strength of low alloy TRIP steels is supported not only by the hardening of ferrite, the major phase as in DP steels, by Si, but also by the compressive residual stress introduced by the expansion due to martensite transformation of retained austenite during cyclic

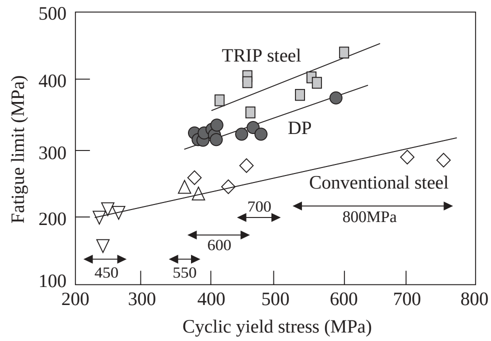

Fig. 9 Effect of cyclic yield stress on fatigue limit of high strength steels

loading[20].

Steels with Cu in solid-solution have also been reported to show very high fatigue limit ratios (fatigue strength/tensile strength), due to the retardation of recovery during cyclic loading[21].

4. Conclusion

High strength steel sheets introduced here have been contributing to the weight reduction and the improvement of crashworthiness of auto bodies in line with the effort of auto manufacturers for the improvement of application technologies. In order to expand the application of high strength steel sheets further in the future, it will be necessary to improve corrosion resistance, shape fixability, and weldability as well as to reduce the flactuations of mechanical properties of steels. It will be important to optimize the materials and the methods of their application through a close cooperation between auto companies and materials suppliers from a very early stage of the development of automobiles such as designing to meet the requirements for automobiles, namely, safety and environmental consciousness.

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