1. Introduction

One of the important tasks for the 21st century is the maintaining of sound ecology. The reduction of the burden on the environment is an inevitable task assigned to industry. Recently, Japan internationally announced that it would reduce the generation of CO₂ by 6% during the 5 years from 2008 to 2012 in comparison with the level in 1990. To satisfy this declaration, the Japanese automotive industry generating around 17% of total CO₂ is now aiming at an improvement of fuel efficiency by 22.8% in 2010 compared with the level in 1995. A direct contribution of the steel industry to the reduction of fuel consumption is the supply of steels enabling the lightening of automotive weight.

Figure 1 shows a relationship between the fuel mileage and automotive weight. The lightening of the weight directly contributes to the improvement of the fuel consumption of cars. While light materials such as Al, Mg and plastics are applied to automotive parts to reduce weight, the application of high strength steel sheets is also promoted because of their advantage that in most cases, the conventional forming technology is applicable without great investment.

Figure 2 shows the strength levels of high strength steel sheets already applied for automotive parts and expected to be applied in the future. The lightening of the weight directly contributes to the improvement of the fuel consumption of cars. While light materials such as Al, Mg and plastics are applied to automotive parts to reduce weight, the application of high strength steel sheets is also promoted because of their advantage that in most cases, the conventional forming technology is applicable without great investment.

In this paper, the recent development of modern high strength steel sheets is reviewed paying special attention to their physical metallurgy which realized the improvement of their formability.

KEY WORDS: high strength steel; formability; BH; TRIP; DP; precipitation hardening; crash worthiness; fatigue resistance; delayed fracture.

Lightening of automobile bodies is required from the viewpoint of saving energy which contributes to ameliorating an ecological problem. A useful means of doing this is the application of high strength steel sheets to automobile bodies. The inferior formability of high strength steel sheets in comparison with that of mild steel sheets, however, hinders their broad application. But in recent years, many high strength steel sheets with good formability have been developed using sophisticated physical metallurgy.

In this paper, the recent development of modern high strength steel sheets is reviewed paying special attention to their physical metallurgy which realized the improvement of their formability.

KEY WORDS: high strength steel; formability; BH; TRIP; DP; precipitation hardening; crash worthiness; fatigue resistance; delayed fracture.
product suffers remarkably. For example, overcooling of TRIP steel sheets causes the martensitic transformation locally and significantly deteriorates the homogeneity of mechanical properties.

Another obstacle concerns their formability. In general, high strength steel sheets have poor formability and often have a narrow or no formable range in press forming for complicated forms. Even though steel sheets are formed without fracture or wrinkles, this is not enough for practical use. Steel sheets are only applicable if the required profile is obtained within certain tolerance by press forming. The profile distortion caused by poor shape fixability such as surface deflection, spring back or distortion hinders the use of high strength steel sheets.

Weldability problems also hinder the wider use of high strength steel sheets. The main problem is the softening of the heat affected zone of welded parts. The softened part becomes a weak point of the material concerning fracture strength and fatigue resistance. Another weldability problem is the formation of blow holes in hot dip Zn coated steel sheets by arc welding often carried out for parts using high strength steel sheets. The blow holes reduce the strength and fatigue resistance.

Concerning fatigue resistance, it must be noted that with higher strength, the fatigue resistance does not increase proportionally to tensile strength and tends to saturate. This means that it is no use applying high strength steel sheets for increasing fatigue resistance if the strength level exceeds more than about 1 000 MPa.

To overcome these problems, much effort has been made. In this paper, the recent development of high strength steel sheets and their physical metallurgy are introduced and future research subjects are discussed.

2. Required Formability of High Strength Steel Sheets

For press forming of automotive bodies and parts, stretch formability, deep drawability, elongation-flangeability and bendability are most important. Because these properties are strongly influenced by microstructure and texture, their control is of great importance.

For high strength steel sheets with a tensile strength level of less than 450 MPa mainly used for outer and inner panels, high stretch formability and good deep drawability are generally key requirements. On the other hand, good elongation-flangeability is often required for high strength steel sheets with a strength level between 450 and 1 000 MPa mainly employed for members, frames, wheels, etc. For ultra high strength steel sheets with a strength level of more than 1 000 MPa, the bendability is an important property.

Another important factor for formability is the planar anisotropy of mechanical properties such as elongation and r-value. Because fracture occurs in the weakest direction, the minimization of planar anisotropy is of practical interest.

As summarized, the development of highly formable high strength steel sheets aims at a steel sheet with required strength and formability by controlling the microstructure and texture using sophisticated physical metallurgy.

3. Modern High Strength Steel Sheets

Figure 4 shows the strength–ductility balance and the strength and hole-expansion ratio balance of various high strength steel sheets. The formability of steel is remarkably influenced by the strengthening mechanism and especially by the resultant microstructure. Therefore, microstructural control is important for obtaining the required formability. In the following, high strength steel sheets whose microstructure is controlled in a sophisticated manner to obtain high formability are reviewed in detail.

3.1. Bake Hardenable (BH) Steel Sheets

BH steel sheets are ideal steel sheets for outer panels of cars because they provide high formability, high surface deflection resistance and high dent resistance simultaneously. The features of BH steel sheet are that it is as highly formable in press forming as mild steel and is subsequently hardened by baking treatment. The baking treatment is usually simulated by a heat treatment at 170°C for 20 min. A BH steel sheet is usually understood to be a steel sheet whose yield strength is increased by a minimum value of 30 MPa by the baking treatment. This increase in strength is based on fixing the dislocations by interstitial atoms such as carbon and nitrogen in solution.

Figure 5 shows the relationships between the BH and the
amount of carbon in solution. With increasing amount of carbon in solution, the bake-hardenability increases. The upper limit of BH is given by the occurrence of the stretcher-strain phenomena due to yield elongation which deteriorates the surface quality of the steel sheet. This limit is around 60 MPa for conventional BH steel sheets.

Kinoshita and Nishimoto showed that BH does not depend only on carbon in solution but also on carbon segregated in the grain boundary. The bake hardening is a strain aging phenomenon which occurs at temperature higher than that at which the natural aging phenomenon occurs. The C segregated at the grain boundary effectively resolves at a higher temperature and contributes to the bake hardening. Figure 6 shows the relationship between aging deterioration and BH for steels with different grain sizes. The grain refinement and the decrease in the amount of elements segregated at the grain boundary competitively with C such as P are reported to raise the limit of BH at which the stretcher-strain phenomena does not occur.

BH treatment at a lower temperature is demanded in order to save energy in production. Tsukatani et al. investigated the influence of Mn and Si content and Fe₃C density on BH using a 130°C and 170°C treatment. They recognized that BH at 130°C reveals two groups as seen in Fig. 7. One group shows that BH is higher than Al while the other shows that BH is less than Al. The former is characterized by a high density of Fe₃C of more than 5×10⁶/mm² and Si content of less than 0.2%. Si influences the distribution of Fe₃C. The increase in the density of Fe₃C increases dislocation density formed by a pre-strain before the BH treatment. The two phenomena realize a relatively high BH even though the amount of C in solution is low.

In the present situation, steelmakers are compelled to guarantee that the stretcher-strain phenomena do not occur at a press forming carried out up to three months after production. Therefore, the maximum BH is limited in practice. The upper limit of BH can, however, be increased if aging is avoided by quick use of the steel sheet having a high amount of carbon or nitrogen in solution after skinpass rolling which introduces mobile dislocations and suppresses yield elongation. For effective application of BH steel sheets, cooperation between steelmakers and automobile manufacturers enabling a strict time schedule from production to press forming is necessary.

There are mainly three methods for producing BH steel sheets. ① Low carbon steel sheets with a limited amount of carbon content are annealed in a batch annealing furnace. ② Low carbon steel sheets are annealed in a continuous annealing line. ③ IF steel sheets are continuously annealed.

In batch annealing processes, steel sheets with a limited amount of carbon fulfill the BH property. If the carbon content is too low, the carbon remaining in solution is not enough to obtain the required minimum BH value. If the carbon content is too high, the precipitation of carbide is
accelerated and the carbon remaining in solution is also too low to obtain the required minimum BH value. A proper amount of carbon is from approximately 0.005% to approximately 0.02%, depending on annealing conditions.

In the case of austenite, a proper amount of carbon is from approximately 0.015% to approximately 0.06% depending on annealing conditions. In a recent development, a continuous annealing consisting of high temperature annealing of approximately 750–800°C, overcooling down to approximately 250–300°C, reheating up to 350–450°C and temperature decreasing overaging has been performed using steel sheets with approximately 0.015% carbon to provide both good formability and bake hardenability.8)

Most BH steel sheets used at the present time are IF steel sheets because of their excellent formability. There are two types of IF-BH steel sheets; the excess C type and the excess Ti and/or Nb type. In the former type, the amount of Ti and/or Nb to be added is reduced so that C in solution remains after the equilibrium formation of carbide with Ti and/or Nb. This method is advantageous in that bake hardenability can be obtained without high-temperature annealing, which is apt to cause heat buckling and requires large energy consumption. However, as C in solution exists during cold rolling, the formation of texture desirable for deep drawability is suppressed, resulting in a lower r-value compared with conventional IF steel sheets.

On the other hand, excess Ti and/or Nb type BH steel sheets exhibit excellent deep drawability as C in solution does not exist during cold rolling, but require high annealing temperature. For this type of BH steel sheet, the solute C required for bake hardenability must be secured by resolving the carbide by high temperature annealing with subsequent rapid cooling. This phenomenon is quantitatively shown in Figure 8 in the case of an Nb-IF steel with Nb/C = 1.58. It will be noted that bake hardenability is enhanced as the annealing temperature and cooling rate are increased.

As BH depends on the amount of the solute C, the fluctuation of the C content caused by the steelmaking process and by picking up in the succeeding processes affects the stability of BH. Figure 9 shows the solubility of NbC at various temperatures. To obtain the same amount of BH, the excess Nb type requires a higher annealing temperature than the excess C type. The fluctuation of solute C of the excess Nb type at the annealing temperature is smaller than that of the excess C type even though the fluctuation of C content in the steels is the same. Consequently, the fluctuation of BH of the excess Nb type is smaller than that of the excess C type. This means that the excess Ti and/or Nb type is preferable from the standpoint of BH stabilization.

Kawasaki et al.9) revealed that bake hardenability of Ti-IF steel is significantly influenced by S and Mn content. If the amount of S is high, the main precipitate with Ti is TiS2C2. On the other hand, if the S content is low, TiC is the main precipitate with Ti. The latter dissolves at lower temperature than the former and as a consequence, Ti-IF with a lower S content has a higher amount of solute C at the time of annealing and shows a higher BH. Even if the S content is high, bake hardenability can be maintained if the necessary amount of Mn is added to form MnS, which hinders the precipitation of TiS2C2.

To obtain stable BH while maintaining relatively high r-value, Yoshinaga et al.10) proposed continuous annealing in the austenite region using Mn added Nb–Ti-IF steel sheets. Figure 10 shows the effect of the annealing temperature on BH and YP-EI of Nb–Ti-IF and 1.5%Mn–Nb–Ti-IF steel sheets. The numerals in the figure mean the transformation ratio. The specimens heated up to the austenite region have a high BH value because the solubility of C in austenite is large. If transformation occurs, YP-EI of 1.5%Mn–Nb–Ti-IF steel is suppressed while that of Nb–Ti-IF steel appears. The fact that YP-EI of high-Mn–Nb–Ti-IF steel becomes zero suggests that the mobile dislocations which cannot be fixed by solute C after aging remain because transformation from austenite to ferrite at a low temperature produced many mobile dislocations.

The r-value at each annealing temperature is shown in Figure 11. In the case of Nb–Ti–IF steel sheets, r-values drastically decrease if the transformation from ferrite to austenite completely occurs. In the case of 1.5%Mn–Nb–Ti-IF steel, r-values are hardly influenced by the occurrence of transformation because the texture after annealing is similar regardless of the occurrence of transformation. The mechanism of the texture memory that the texture does not change in high-Mn–Nb–Ti–IF steel sheets even though they underwent transformation may be due to the effect of residual transformation stresses.10) Showing that the texture memory is hardly weakened by prolonged annealing where grain growth occurred and residual transformation stresses probably were decreased, Hutchinson et al.11) suspected the residual stress hypothesis.

Although this technology has the advantage of obtaining high BH without YP-EI, the r-value of this steel is lower than that of conventional IF steel such as Nb–Ti–IF in Figure 11 because the high amount of Mn lowers the r-value.

Kimura et al.12) proposed a new technology by which bake hardenability is imparted to Ti-IF steel keeping a high r-value by carbonizing at the time of continuous annealing. Figure 12 shows the influence of carbonizing time at 850°C on the amount of C added and on the BH of IF steel sheets with a Ti content of 0.021% and 0.031%, respectively. It is clearly seen that the BH increases with the increasing amount of C added by carbonizing but the increase in the BH is moderate if the amount of Ti content is high because C then becomes carbide and cannot remain in solution. If the carbonizing is carried out after completion of recrystallization, the r-value is not lowered.

3.2. Surface Hardened Dent Resistant Steel Sheets

Another technology has been introduced to improve the dent resistance without deteriorating the r-value. The key technology is the nitriding or carbo-nitriding of Ti bearing IF steel at the time of continuous annealing in NH3 containing atmosphere.13) The difference of this technology from that of carbonizing lies in the formation of a significantly hardened surface layer. The hardening of the surface layer occurs by the formation of clusters or fine precipitates consisting of titanium and nitrogen.

Figure 13 shows the change in hardness in the thickness direction with increasing nitriding time. The concentration of ammonia is 4%, the nitriding temperature is 750°C and the nitriding time is varied 0, 20, 40, 60 sec. It is clearly seen that the hardened layer quite rapidly forms and extends...
This hybrid structure provides high dent resistance because the hardened surface layer increases the bending resistance and consequently the dent resistance. Figure 14 shows the relationship between the dent resistance and yield strength of nitrided Ti bearing IF steel sheets compared with conventional IF steels. The nitriding temperature is 750°C, the nitriding time is varied 20, 40, 60 sec, the concentration of ammonium is varied 1, 2, 4, 10, 20 %, and the Ti content is 0.046 %. The steel sheets marked 28 and 38 K are conventional IF steel sheets with TS of 280 and 380 MPa, respectively. Although the BH of the nitrided IF steel sheets was only around 25 MPa, the nitrided IF steel sheets show significantly higher dent resistance than conventional IF steel sheets with the same YP. So, this technology offers high dent resistance without worsening the surface deflection which is mostly controlled by YP.

The diffusion and precipitation behaviors of nitrided steel sheets were modeled and the mechanism of the precipitation hardening of TiN is discussed elsewhere.14) 3.3. DP (Dual Phase) Steel Sheets

The microstructure of dual phase steel sheets consists of a ferrite matrix with dispersed martensite. The DP steel sheets are made ductile by the ferrite and their strength is controlled by the amount of martensite therein. The properties of the steel can be controlled in accordance with the amount of martensite as seen in Fig. 15.15) Besides a good strength and elongation balance, DP steel sheets are characterized by a markedly low yield ratio and by the absence of YP-El. Although YP-El does not appear, we obtain high BH up to 100 MPa. It means that a remarkably high BH is achievable without the occurrence of the stretcher strain phenomenon. These phenomena can be explained by the existence of mobile dislocations around dispersed martensite.
site formed by martensitic transformation.\textsuperscript{16)}

DP steel sheets are produced either by hot rolling or cold rolling followed by continuous annealing. To obtain good formability, the ferrite matrix should be soft, which is realized by ferrite transformation of the steel sheets at a high temperature. Afterwards, the steel is rapidly cooled below Ms temperature to suppress the formation of pearlite and bainite.

It has been recently reported\textsuperscript{17)} that DP steel with finely dispersed martensite improved the crashworthiness of cars. Figure 16 shows the influence of a ferrite-martensite perimeter on dynamic absorbed energy by a deformation at a strain rate of $2 \times 10^3$ sec\(^{-1}\). The ferrite–martensite perimeter is defined as a length of the ferrite–martensite interface in the unit area of $1 \, \text{mm}^2$. With the lengthening of the ferrite–martensite perimeter, dynamic absorbed energy increases. This means that the dynamic absorbed energy increases if the martensite is finely dispersed. In deformation at a low strain rate of $2 \times 10^2$ sec\(^{-1}\), this dependence cannot be recognized, that is, the amount of the deformation energy hardly depends on the dispersed state of martensite.

DP steel sheets contain a high amount of C and/or N in solution due to rapid cooling to a low temperature of around 150°C. BH treatment of DP steels, therefore, increases the strength of the steel significantly and thus substantially improves the crashworthiness of cars.

Figure 17 shows a unique feature of DP steel sheets that the BH increases upon increasing WH, which is uncommon for other steels.\textsuperscript{18)}

3.4. Residual Austenite Steel Sheets

Residual austenite steel sheets are also called TRIP (Transformation induced plasticity) steel sheets produced either as hot bands or cold rolled products. TRIP steel sheets are most formable steel sheets in the strength level higher than 600 MPa because of TRIP phenomena. For the TRIP phenomena, quasi-stable austenite is needed at room temperature. The quasi-stable austenite transforms into martensite by forming and the transformed part is strengthened so that strain localization is avoided resulting in the improvement of ductility.

Figure 18 shows the concept for obtaining quasi-stable...
austenite at room temperature in the case of cold rolled product. In the inter-critical annealing, C in austenite is enriched according to the equilibrium condition and during the progress of ferrite transformation, C concentration in austenite increases. If pearlite transformation is suppressed by rapid cooling and the cementite precipitation during bainite transformation is avoided by adding Si and Al, C in austenite is enriched up to the concentration for To where the free energy of ferrite is equal to that of austenite in consideration of strain energy caused by transformation. Because To depends on the chemical composition, the saturated C concentration in austenite after completion of bainite transformation also depends on the chemical composition. For example, Mn decreases the C concentration of retained austenite. If the concentration of C in austenite reaches around 1.2%, the austenite becomes quasi-stable at room temperature.

The processing of TRIP steel sheets is similar to that of DP steels. A significant difference between the two steel sheets is the cooling temperature for hot rolled products or over-aging temperature for cold rolled products. The temperature is around 150°C for DP steels and around 400°C for TRIP steels where the bainite transformation proceeds.

Figure 19 shows the change in the properties of cold rolled TRIP steel sheets during over-aging in a continuous annealing process. It is recognized that the strength–ductility balance is more closely related to the concentration of C in austenite than to the amount of retained austenite. This indicates that the plastic stability of retained austenite plays an important role regarding the good strength–ductility balance of TRIP steel sheets. It has been proved that the strain induced transformation of austenite is retarded if the C content in it is high and as a consequence, the strain induced transformation lasts in a high strain region, which contributes to diffusing the strain concentration, resulting in a more uniform elongation. A mathematical model evaluating the stability of retained austenite and describing the kinetics of strain induced martensite transformation has been proposed and the increase in the stability of retained austenite upon C content being increased has been quantitatively evaluated. The decrease in the amount of retained austenite during deformation depends on the forming mode. The amount of retained austenite of a specimen which undergoes shrink flanging is higher than that of a uni-axially or equi-biaxially deformed specimen after deformation at the same equivalent strain. Hiwatashi et al. proposed that the difference can be explained by considering the hydrostatic pressure acting in the forming and concluded that the stability of the retained austenite is controlled by the equivalent strain and the hydrostatic pressure. The better deep drawability of TRIP steel sheets determined by cylindrical drawing test than the other high strength steel sheets with the same r-value was explained by the difference in TRIP phenomena based on the different forming mode. The wall of a cylindrical drawing specimen undergoes uni-axial strain forming while the flange is formed by shrink flanging mode. The flange is less strengthened by TRIP phenomena than the wall, resulting in the less drawing resistance of the flange and better deep drawability.

Figure 20 shows the formable range of various steel sheets for the formation of a door model as an example of the excellent formability of TRIP steel. Steel A is a TRIP steel, Steel P is a precipitation hardened steel, Steel D is a DP steel and Steel S is a solution hardened steel. The TRIP steel shows the widest formable range among tested steel sheets. In this case, Steels P and D having the same strength level as that of Steel A possess no formable range. The good strength–ductility balance of TRIP steel enables application of a large blank holding force without rupture. The large blank holding force contributes to the stabilization of the required shape of the product.

Regarding materials used for the structural parts of an automobile, the fatigue resistance thereof is one of the key factors for determining the thickness of the steel sheet. Figure 21 shows the fatigue strength of steels with various microstructures. The parameter in the figure means the micro-constituents, F: ferrite, B: bainite, M: martensite, P: pearlite. The TRIP steel marked with □ shows a higher fatigue strength than the other steel sheets with the same TS level. The fact that the volume fraction of retained austenite decreases during the stress controlled fatigue test indicates that the localized transformation of retained austenite into martensite at a tip of a fatigue crack improves the fatigue resistance. The
reason is that the localized transformation increases the resistance to the crack growth due to significant work hardening occurring in front of the crack and due to the formation of compressive stress associated with the volume increase caused by the transformation.

Another important property of high strength steel sheets is a capacity for collision impact energy absorption. Good high strength steel sheets possess both good formability and high capacity for impact energy absorption. Figure 22 shows the relationship between the quasi-static flow stress at 5% strain as a representative value of formability and the calculated value of absorbed energy until 10 msec after a collision.26) The TRIP steel sheet and the DP steel sheet possess both good formability and a high capacity for impact energy absorption and the application of these steel sheets contributes to improve the crashworthiness of automobiles. The reason why these steel sheets improve crashworthiness lies in their high strain rate sensitivity, high work hardenability and high bake hardenability.

3.5. High Strength Steel Sheets with a High Hole Expanding Ratio

To obtain a high hole expanding ratio, the formation of a homogeneous microstructure is important. The hole forming is usually carried out by punching or piercing. The quality of the punched surface in the hole depends on the punching condition and microstructure of the steel sheet. The punched surface consists of sheared and brittle fractured parts. Because the brittle fractured part contains more micro-cracks than the sheared part, the smaller the ratio of brittle fractured part/sheared part is, the higher the hole expanding ratio is. Micro-cracks are often observed in a softer micro-constituent in the vicinity of harder micro-constituents because the strain concentrates there. The existence of the micro-cracks reduces the hole expanding ratio. Steels showing inhomogeneous microstructure whose micro-constituents have a quite large difference in hardness are ferrite–pearlite steels, DP steels and TRIP steels. On the other hand, steels showing relatively homogeneous microstructure are single phase ferrite steels, bainitic ferrite steels, bainite steels, etc. Figure 4 shows that the steels with homogeneous microstructure have a markedly higher hole expanding ratio than those with inhomogeneous microstructure.

Besides microstructure, it is known that the addition of Si and P influences the hole expanding ratio. Adding a proper amount of Si improves the hole expanding ratio. Si increases the strength of ferrite and decreases the difference in strength between ferrite and second phase particles. The addition of Si promotes the formation of polygonal ferrite which also contributes to improve the hole expanding ratio. On the other hand, P segregated at grain boundaries decreases the hole expanding ratio.

There are several new developments of high strength steel sheets with a high hole expanding ratio. One development is based on the precipitation hardening of single ferrite phase steel sheets. To significantly increase the strength of steel sheets by precipitation hardening, a large amount of fine precipitates is necessary. Figure 23 shows a process for producing hot rolled high strength steel sheets with a high hole expanding ratio.27) Adding a relatively high amount of Ti of around 0.1 to 0.2% to a low carbon steel with a carbon content of around 0.05 to 0.1%, the ferrite matrix is strengthened by TiC precipitated in a considerable amount during and just after ferrite transformation during slow cooling. Because the precipitates are small, strain localization hardly occurs in their vicinity and the tendency to form micro-cracks is reduced.

As an application of this technology, a steel sheet with bainitic ferrite microstructure is strengthened by TiC precipitated in an off-line heat treatment to improve the strength–hole expanding ratio balance.28) Instead of TiC, Cu precipitates are used to produce a high strength steel sheet with a high hole expanding ratio.
according to the same principle mentioned above. In this case, the precipitation of Cu is carried out in the coiling process for hot bands and in the over-aging process for cold rolled products. Figure 24 shows the influence of aging time and temperature on the tensile strength of 1.6% Cu containing IF steel sheets. It is recognized that a strength increase of around 200 MPa is realized by a relatively short time heat treatment. The precipitates strengthening the steel are bcc-Cu with a size of several nanometers. If the precipitates become large and change into stable fcc-Cu, the precipitation strength drastically decreases.29)

Another development for improving the hole expanding ratio of steel sheets with inhomogeneous microstructure is based on the concept that the difference in strength between ferrite and hard second phase such as martensite and retained austenite by strengthening the ferrite matrix with finely dispersed precipitates. Figure 25 shows a process for improving the hole expanding ratio of DP steel sheets.30) The principle is the same as shown in Fig. 23. Adding a proper amount of Ti of around 0.1% to a conventional DP steel, the ferrite matrix is strengthened by TiC precipitated just after ferrite transformation during slow cooling. The decrease in the difference between the strength of ferrite matrix and that of the martensite reduces the local strain concentration in ferrite and improves local elongation and the hole expanding ratio.

On the other hand, the improvement of the hole expanding ratio of TRIP steel sheets was carried out by changing the microstructure consisting of ferrite, bainite and retained austenite into that of bainite matrix with film-like retained austenite.31) The concept is as follows: 1. The homogeneity of the microstructure is increased by forming bainitic or bainitic ferrite microstructure as the main microstructure. 2. The stability of retained austenite increases by reducing the amount of austenite. Most of the stabilized austenite is not transformed into martensite during the punching process and first transformed during hole expanding. The TRIP phenomenon during punching enhances the difference in the strength of micro-constituents and promotes the forming of micro-cracks and deteriorates hole expanding ratio. On the contrary, the TRIP phenomenon during hole expanding prevents strain localization and suppresses the growth of micro-cracks, resulting in good hole expanding ratio. Although this kind of the TRIP steel sheet has a significantly lower elongation than conventional TRIP steel sheet with the same strength level, it is reported that the stretch formability is hardly worsened. This surprising phenomenon is now being critically re-examined.

3.6. Deep Drawable High Strength Steel Sheets

In general, high strength steel sheets with a tensile strength of more than 600 MPa possess poor deep drawability. Recently, a deep drawable high strength steel sheet was developed using two well-known facts: cold rolled IF steel sheets show excellent deep drawability, and Cu in steel shows high solubility in austenite and precipitates finely at a relatively low temperature and strengthens the steel significantly, as shown in Fig. 24. By preventing the precipitation of finely dispersed Cu in the coiling process and hardening by precipitation in the over-aging process in a continuous annealing line, a deep drawable high strength steel sheet was developed using a Cu bearing IF steel. Figure 26 shows the influence of the coiling temperature on the r-value of cold rolled Cu bearing IF steel sheets. If Cu is coarsely precipitated at high coiling temperature or the precipitation of Cu is suppressed at low coiling temperature, cold rolled steel sheets with an r-value of around 1.5 are achievable.32) The existence of finely dispersed Cu in hot bands hinders the formation of texture desirable for good deep drawability of cold rolled products.

This steel sheet is characterized not only by good deep drawability but also by a high hole expanding ratio as mentioned in Sec. 3.5. Another good feature of Cu-bearing high strength steel sheets is their high fatigue resistance. That is, Cu in solution retards the formation of cells in the dislocation structure, which is considered to retard the initiation of fatigue cracks.33)
A drawback of the Cu-bearing steel is that expensive Ni needs to be added to prevent the occurrence of surface cracks caused by the Cu-rich liquid phase in the grain boundary in the vicinity of the surface during hot rolling.\(^{34}\) Besides, Cu is an element which is very difficult to remove in the refining process and has a detrimental effect on steel recycling.\(^{35}\)

### 3.7. High Strength Steel Sheets with High Fatigue Strength at Welded Parts

One of the factors hindering the broad application of high strength steel sheets is the apparent softening of the heat affected zone (HAZ) of welded parts. The softened part is a potential source of fracture by forming and by fatigue. The softening of the HAZ hinders the increase in strength and fatigue resistance expected by the use of high strength steel sheets.

To prevent the softening, an Nb and Mo bearing high strength steel sheet was developed.\(^{36}\) The feature of this steel is that multiple component precipitates consisting of Nb, Mo and C rapidly precipitate in the HAZ during the welding process and prevent the softening. The reason why rapid precipitation is possible is that Mo suppresses the annihilation of the dislocations introduced by deformation in the HAZ during the welding process and the precipitation is promoted by the increase in nucleation sites and by pipe diffusion through dislocations.

### 3.8. High Strength Steel Sheets with Ultra-fine Ferrite Microstructure

From the viewpoint of recycling, the use of alloying elements should be avoided and the development of high strength steel sheets with plain carbon composition should be promoted. In the STX-21 project lead by the National Research Institute in Japan,\(^{37}\) a high strength steel sheet with a tensile strength of 800 MPa is being developed by grain refinement of a conventional 400 MPa steel sheet from around 10 \(\mu m\) to around 1 \(\mu m\). To realize this kind of significant grain refinement, heavy reduction hot rolling processes in the unstable austenite region, inter-critical temperature region and ferrite region are proposed.\(^{38-40}\) The deformation induced transformation and dynamic recrystallization of ferrite greatly contribute to the remarkable grain refinement of this TMCP. Even in a stable austenite region above \(\mathrm{Ae}_3\), it was reported that a heavy reduction induces the massive transformation and produces an ultra-fine ferrite microstructure.\(^{41}\)

To obtain a sub-micrometer ferrite microstructure, a minimum reduction of 70% is required for one-pass deformation and 50% for multi-pass deformation. These high-reduction operations are not realistic in practice. The reasons are: 1. Required accuracy of gauge is difficult to achieve. 2. The temperature increase due to heavy reduction at the commercial high speed rolling can cause grain coarsening instead of grain refinement. 3. Most of the conventional mills lack the necessary power. Under a pass schedule realized in practice, the achievable minimum grain size is around 2 \(\mu m\) even if the residual strain effect is fully used.\(^{32}\)

The mechanical properties of the high strength steel sheets with ultra fine ferrite microstructure have been examined and improvement of the strength–toughness balance and of fatigue resistance has been confirmed. Their strength–ductility balance is, however, inferior to that of DP and TRIP steel sheets. Besides, the high yield strength of this steel sheet based on the Hall–Petch relationship is detrimental for profile fixability by press forming. Another drawback of this steel sheet is the occurrence of softening caused by coarsening the ultra fine ferrite grains in the heat affected zone of welded parts. To suppress the grain coarsening, proper precipitation treatment is needed.\(^{43}\)

Although a lot of effort has been made in the STX-21 project to improve the drawbacks of these steel sheets, in the present state, the application of high strength steel sheets with ultra fine ferrite microstructure for automotive parts is quite restricted.

### 3.9. Super High Strength Steel Sheets

Super high strength steel sheets whose tensile strength is more than 1000 MPa are used for bumper reinforcements, door impact beams, etc. Yamazaki et al.\(^{44}\) showed that in the case of a hot type press forming, the formability of super high strength steel sheets can be evaluated by bendability and investigated the relationship between bendability and microstructure of these sheets. It was found that bendability strongly depended on the homogeneity of the microstructure, not on ductility and strength, as shown in Fig. 27. Initial cracks were found mainly at the interface between soft micro-constituents and hard micro-constituents.

To obtain a homogeneous microstructure of hot rolled super high strength steel sheets, it is important that the increase in C concentration in austenite during cooling is suppressed by means of rapid cooling. For cold rolled products, intercritical annealing should be avoided so that the enrichment of C in austenite is suppressed. The inhomogeneity of the microstructure means that there are many local sites in which micro-cracks can nucleate. If there are initial cracks in the product caused by inclusions or scratch damage, bendability is significantly deteriorated.
On the other hand, super high strength steel sheets are susceptible to delayed fracture. As shown in Fig. 28, delayed fracture is likely to occur upon the amount of retained austenite being increased. It is thought that the reason for this is that the volume increase caused by strain induced transformation from retained austenite into martensite can form voids or high intensity of dislocations in the vicinity of the transformed martensite, and hydrogen gathers in these places, leading to fracture. To reduce the retained austenite, annealing in the austenite range is preferable to inter-critical annealing.45)

3.10. Zinc Dip Coated High Strength Steel Sheets with High Formability

A problem related to high strength steel sheets is that the elements added to strengthen the steel often cause dip-coating defects and/or suppress the galvannealing reaction. Phosphor used as a solute hardening element, for example, enhances the formation of Fe–Al which impedes the galvannealing reaction.46) The addition of Si, which improves the strength–ductility balance, causes the formation of a firm silicon oxide film which decreases the wettability of dip-coating and leads to coating defects.47) To improve the wettability and avoid coating defects, a pre-coating technique is sometimes employed. Ni-, Cu- and Fe-pre-coatings are reported to improve the wettability of Si bearing high strength steel sheets.48)

Concerning the metallurgy in a continuous galvannealing line (CGL), the influence of the heating condition, the cooling condition after heating and the galvannealing condition on mechanical properties were mainly investigated. The first two conditions are common subjects regarding the continuous annealing process, but the last one is a unique problem in the CGL process. The galvannealing process can deteriorate the mechanical properties of steel sheets. A representative example is TRIP steel sheet. During the galvannealing process, Fe3C can be precipitated and the amount of retained austenite and the concentration of C in it are reduced. Therefore, to produce TRIP steel, alloying elements which suppress the precipitation of cementite should be increased.

High strength steels used for member parts are often arc-welded. In this case, blow holes are formed in zinc dip coated steel sheets, which deteriorate the strength and fatigue resistance of welded parts. To suppress blow hole formation, welding conditions are optimized, but great success has not been achieved yet.49) To enable the broad use of zinc dip coated high strength steel sheets, the problem related to arc-welding must be solved.

3.11. Further Development of High Strength Steel Sheets

High strength steel sheets to be developed further for extending their use to automotive parts are given in Fig. 29. All the developments are very challenging but without these new developments, wide application of high strength steel sheets to automotive parts cannot be expected.

4. Stable Manufacturing Method

Upon high strength steel sheets being formed, practical use thereof is not possible if the required shape is not obtained within the required gauge accuracy, even if fractures or wrinkle formation does not occur. Deviation from the required shape generally increases with increasing strength due to the spring back effect. Even for high strength steel sheets, a shape with the required accuracy can be obtained if the spring back effect is properly considered in the tooling design. In this case, however, the fluctuation of the gauge and strength of the steel sheet must be controlled to a certain tolerance. Figure 30 shows that the fluctuation of strength generally increases with increasing strength if no controlling measure is met.

Recently, a technology to increase the gauge accuracy and to decrease the fluctuation of strength was developed. Figure 31 shows the principle of the technology for controlling the strength of hot rolled products.50) This technolo-
gy consists of software determining the strength from microstructural factors predicted by a metallurgical model, and hardware minimizing the fluctuation of strength by controlling the hot rolling and/or cooling condition. This technology makes it possible to obtain the required strength within a certain tolerance. Besides, this computer controlled system also predicts the resistance to hot deformation accurately by considering the evolution of microstructure and as a consequence contributes to increasing the gauge accuracy of products. Such a computer controlled system has been already installed in modern steelworks.

Another way to minimize the fluctuation of strength is realized by the development of sophisticated new hot strip mills. Kawasaki Steel’s Chiba Works and Nippon Steel’s Ohita Works realized endless hot rolling by welding the hot bar before finishing rolling. This technology makes it possible to minimize unsteady operation in the top and bottom regions of hot strips, enables nearly isothermal hot rolling at a constant speed and realizes a product with minimum fluctuation of strength. Endless hot rolling is expected to be applied in mini-mills as well.

Besides, endless rolling enables highly lubricated hot rolling because the roll biting problem of each hot bar can be avoided by cutting lubricant only at the top of the first hot bar. Lubricated hot rolling reduces the rolling load and torque and enables low temperature rolling which often improves the mechanical properties of high strength steel sheets because of the grain refinement, but is usually difficult to carry out for high strength steels because of their high resistance to hot deformation. Another advantage of lubricated hot rolling is the decrease in the frequency of surface defects.

Recently, deep drawable hot bands were developed by lubricated hot rolling of IF steel sheets in the ferritic temperature range. Lubricated hot rolling reduces the shear strain in the surface region of hot bands and changes the surface texture deteriorating the r-value to that similar to midlayer texture desirable for deep drawability. An r-value of around 2 was obtained for a hot band of 1mm in thickness hot rolled at around 750°C in the laboratory. Using a deep drawable hot band, the deep drawability of cold rolled steel sheets can be improved significantly. For example, using a hot band with an r-value of around 1.5, a cold rolled steel sheet with an r-value of around 3 was produced. The deep drawability of Cu bearing high strength steel sheets mentioned in 3.6. can also be improved using this technology.

5. Means Supporting the Increase of the Use of High Strength Steel Sheets

If a steel sheet can be formed without fractures and wrinkles and within tolerable gauge accuracy, it is due very much to forming technique. For example, as mentioned in the Introduction, the ULSUB-project achieved around 25% weight reduction of a white body mainly by sophisticated use of forming technology. The forming technology contributing to proper formation of high strength steel sheets is, from the viewpoint of hardware, the hydroforming, tailored blanking, warm press forming, etc., and from a viewpoint of software, forming simulation with FEM to optimum tooling design and material selection. One of the largest problems in the press forming of high strength steel sheets is poor shape fixability. To improve shape fixability, the following techniques are employed: 1. re-striking or re-pushing, meaning an additional light pressing after conventional press forming, 2. press forming with dynamically controlled blank holding force, 3. press forming at high temperature, 4. press forming + post heat treatment, meaning that a mild steel sheet is press-formed and strengthened afterwards by heat treatment, etc.

Tribology is another means for extending the apparent formability of high strength steel sheets. The practical formability of automotive steels is often affected as much or more by superficial properties such as interfacial friction with the tooling as by the inherent formability of the steel. It is well known that the reduction of friction between the product and tooling due to proper lubrication improves the formability, especially deep drawability. In the use of liquid lubricants, a proper control of roughness improves forma-
bility because the lubrication effectively works due to the lubricant existing in the properly roughened surface.

Besides liquid lubricants, the use of solid film lubricants is increasing because of their extremely low coefficient of friction and of environment friendly property. There are two types of solid film lubricants. One is the solid film lubricant removed after press forming and the other is that remained and painted thereon. Solid film lubricants should provide proper interfacial friction with tooling, good coating property, anti-corrosion property, good weldability, good paintability, reasonable price, etc. For the solid film lubricant removed after press forming, the removability of the film is also important.

6. Conclusion

In this paper, the recent developments of modern high strength steel sheets were reviewed paying special attention to their physical metallurgy. As shown here, a series of highly formable new high strength steel sheets have been developed using sophisticated physical metallurgy and have contributed to expanding the application of high strength steel sheets, especially to automobile bodies and parts.

Besides further developments of new types of high strength steels with better mechanical properties, the development of proper forming and welding technology is required to expand the use of high strength steel sheets. Therefore, a key to extending the use of high strength steel sheets for automobile parts is the cooperation of the automotive industry and steelmakers in developing materials and forming and welding technologies simultaneously. A new concept ‘early involvement and concurrent engineering’ being carried out through the joint efforts of the automotive industry and steel industry leads us to expect a promising future.

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