Metallurgical Factors Affecting the Formability of Cold-rolled High Strength Steel Sheets*

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Synopsis

The metallurgical factors affecting the press formability of cold rolled high strength steels are discussed and the properties of the following 40 kgf/mm² class tensile strength steels are examined: dual phase steel consisting of a ferrite-martensite structure, produced by rapid cooling in a continuous annealing line, which has a very low yield to tensile strength ratio and high m-value; rephosphorized steel, which is a batch-annealed aluminum-killed steel hardened with phosphorus and manganese, having a high r-value and a relatively low yield strength; and a recently developed steel of extra deep drawing quality and high strength which is characterized by its extremely high r-value, over 2.0, and low yield strength. This can be produced by continuous annealing of niobium-stabilized, extra low carbon, phosphorus-bearing steel. The formability and brittleness of the steels are also examined.

I. Introduction

The biggest obstacle to using high strength steel sheets for automobile body components, so as to reduce weight and improve safety, is the problems involving press formability. This report discusses three types of steels: dual phase steel, rephosphorized steel, and extra deep drawing high strength steel, with emphasis on the metallurgical characteristics of cold-rolled high strength steel sheet possessing good press formability. The first two steels are well known and widely accepted, and the last has been recently developed. Various metallurgical factors affecting the formability of these steels are also discussed.

II. Dual Phase Steel

Yield strength (YS) is one of the major factors influencing the press formability of steels. For instance, the reason why decarburized and denitrogenized steel produced by open coil annealing possesses a higher degree of formability than ordinary Al-killed steel is not only because the former steel has a greater elongation (El), by 3~4%, but also because it possesses a lower yield strength, by 3~4 kgf/mm², in comparison with the latter.1) However, when solution hardening elements such as Mn and Si are added for the purpose of increasing the tensile strength (TS), the YS increases with the TS.

Normally, the yield ratio (YR=YS/TS) of solution-hardened steels is 60~70%. However, when steel sheets containing Mn, Cr, Mo, etc., are subjected to rapid cooling following continuous annealing, the YR decreases to approximately 50%, and moreover, the YS increases sharply with strain aging.2) This means that the forming of these steel sheets can be easily performed because of their low yield strength at the time of press forming, and that their yield strength then increases after forming, coating, and baking. Austenite is present when a steel sheet is being annealed above the Ar temperature, and this austenite transforms into martensite during the rapid cooling stage. As a result, such steel sheet exhibits a dual phase structure, i.e., martensite islands dispersed in a ferrite matrix. The strength of this steel sheet depends on the volume fraction of the martensite. For example, 40 K steel (tensile strength approximately 40 kgf/mm²) is produced when the amount of martensite is 2~5%, while 100 K steel is obtained when the martensite is increased to several tens of percent.

The relationship between the critical cooling rate (CR), which is the minimum necessary to form the dual phase structure, and the amount of alloying elements is shown in Fig. 1. One specimen contained 0.05%C and 0.6~1.7%Mn, and a maximum of 0.5% Cr or Mo was added to the other two specimens, with 0.05%C and 1.2%Mn. The specimens were cold rolled and were then subjected to a one minute heat treatment at 770°C and then cooled at 5~2 000°C/s.

In order to obtain a dual phase structure, the CR must be increased if the amounts of the alloying elements are decreased. For example, the CR in a 0.6%Mn steel is one-hundred times that in a 1.7%Mn steel. The effect of Cr and Mo on the critical cooling rate is 1.3 and 2.7 times that of Mn, respectively.

![Fig. 1. Relationship between the critical cooling rate and the amount of alloying elements.](image)

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1. Effects of Alloying Elements and Cooling Rate on Yield Strength

As shown in Fig. 1, the critical cooling rate required for the formation of the dual phase structure is not affected by replacing Mn, Cr, or Mo by one another. However, the influence of alloying elements such as Mn, Cr, and Mo on the tensile properties is not necessarily the same. The effect of cooling rate on the tensile properties of steel with Cr additions is shown in Fig. 2. The tensile strength increases with increasing cooling rate and there exists an optimum cooling rate which minimizes the necessary alloying content. The range of near-optimum cooling rates where the required lower YS is obtained is wider in steel with a higher Cr content.

The effects of cooling rate and alloying content on the 50% equi-YR and 22 and 25 kgf/mm² equi-YS curves are shown in Fig. 3. In regard to steels to which Mn, Cr, and Mo are added, both the equi-yield to tensile strength ratio (equi-YR) line and the equi-yield strength (equi-YS) lines form downward curves. These curves show that the percentage of alloying elements must be increased in order to achieve a lower YS, and that each curve has an optimum cooling rate that requires the least amount of additives. Arranged in inverse order of optimum cooling rate, Mo is the slowest, followed by Cr, and then by Mn. However, whereas a low yield strength is attainable with Cr over a wide range of cooling rates, the range is narrower with Mn. Moreover, in the case of the steels with Mn additions, it is necessary to keep the cooling rate in the range 50~100°C/s in order to obtain a YS lower than 25 kgf/mm².

The reasons for the existence of an optimum cooling rate allowing a minimum alloy content are as follows:

1) In the slower cooling region, a large alloying content is necessary to stabilize the austenite in the martensite transformation.

2) In the faster cooling region, the ferrite matrix is strengthened by the larger quantity of dissolved C due to the decrease in the time available for diffusion into the austenite.

In this latter case, the alloying elements decrease the solubility of C in the α+γ temperature range and strengthen the ferrite. However, both effects will be balanced at a particular cooling rate.

A minimum yield strength of 22 kgf/mm² is obtainable from steels with Mn or Mo additions, but it is possible to obtain yield strengths of less than 20 kgf/mm² with Cr additions. The reason for this is that, as shown in Fig. 7, the solution hardenability of Cr is less than that of Mn or Mo.

2. High Ductility

Both dual phase steels (DP) and ferrite-pearlite steels (F+P) were made from the same alloy by changing the cooling rate after annealing, and the mechanical properties in the annealed state were compared. YS, TS and El for these steels are shown in Fig. 4. The YS is obviously lower in the DP steel than in the F+P steel, but the El is somewhat higher at the same TS. Furthermore, temper rolling must necessarily be performed on F+P steels after annealing in order to extinguish the yield point elongation, whereas such treatment is unnecessary for DP steels. For example, Fig. 5 illustrates the changes in tensile properties when temper rolling was performed on a DP steel in order to regulate the surface roughness and to readjust the flatness. Although the TS hardly changes, the YS, El and the work hardening rate (n-value) deteriorate with an increase in reduction, and for the usual reduction rate of 0.8%, the YS increases by ap-

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Fig. 2. Effect of cooling rate on yield and tensile strengths in Cr-bearing steels.

Fig. 3. Effects of cooling rate and amount of alloying elements on equi-YR curves and equi-YS curves. (basic composition: 0.05%C-1.2%Mn)
approximately 4 kgf/mm², while the E1 and n5-15 decrease by approximately 3% and 0.5, respectively.

In case of ferrite-pearlite steel, the necessary temper-rolling after annealing results in lower elongation values than those shown in Fig. 4. A low yield to tensile strength ratio, a high elongation, and a high work hardening rate in the small strain range are special characteristics of DP steel, and the reason for these characteristics is that no cold working is performed (or rather, cold working is unnecessary) on the steel after annealing.

3. Large Bake Hardenability

The strain aging properties of dual phase steel containing Cr are compared with those of aluminum-killed steel (DDQ) in Fig. 6. The YS of the DDQ increased by about 9 kgf/mm², from 18 kgf/mm² to 27 kgf/mm², as a result of a 20-min aging at 170°C after 5% prestraining. On the other hand, the YS of the DP steel increased by approximately 21 kgf/mm², from 21 kgf/mm² to 42 kgf/mm², providing good performance as regards dent resistance. If a high-temperature bake coating could be developed, the YS would show further an improvement of approximately 3 kgf/mm². Another advantage of DP steel is an improvement in the TS of approximately 10% during the period of strain aging.

III. Rephosphorized Steel

Since the DP steel discussed above possessed a low r-value of 0.9~1.1, it is not suitable for deep drawing parts.

Both in the case of the solution hardening method and in the case of strengthening by transformation, some type of alloying element is added to steels to increase the TS. However, these additives cause
changes in the El and YS. Figure 7, obtained through regression analysis, shows the effect of the strengthening elements generally used, C, Si, Mn, P, and Cr, on the T3, YS, and El of steel sheets which were box-annealed at 670°C for 10 h following cold rolling to a thickness of 0.8 mm. In Fig. 7, an increase in T3 is accompanied by a decrease in El. In terms of the size of the decrease in El accompanying a given increase in T3, Si gives the smallest change, followed by P, Mn, and then C, in that order. These elements exhibit the same tendencies in the relationship between YS and El. The increases in the T3 are in proportion to those in the YS and therefore the ratio of YS to T3 remains almost constant. Among these elements, P is well known for its favorable effects in the improvement of the texture of cold-rolled steel sheets. Taking advantage of P being only second to Si in the smallness of the size of the decrease in El relative to the increase in T3, a high strength steel with better deep drawability than that of rephosphorized steel is required.

In order to produce such an extra deep drawing high strength steel, the addition of solution hardening elements to an extra deep drawing mild steel is suggested, for example, an extra low C Ti-killed steel with an r-value larger than 2.0. However, when P is added to strengthen such a Ti-killed steel, the r-value deteriorates sharply (1.5~1.6). When Mn or Mn+Si is added for the same purpose, an r-value of approximately 1.8 can be obtained in this steel, the same as that of an ordinary rephosphorized steel.

Besides Ti, there are other carbonitride formers such as Nb, Zr, etc. Excessive addition of Nb (free Nb ≥ 0.025%) relative to the equivalent atomic ratio of C and N in extra low C steel produces a high r-value of over 2.0. However, the amount of P added must therefore be limited to approximately 0.1%, and is supplemented with Mn when a higher strength steel is desired. Although Si would be more favorable than Mn from the standpoint of elongation, Si is easily oxidized and liable to generate temper color during box annealing. Additionally, even though C is the least expensive of the strengthening elements, the ductility ratio (cross tension strength/tensile shear strength) following spot welding decreases to 50% or lower when the C content exceeds 0.10%, as is shown in Fig. 8. The likely reason for this is that the high cooling rate following spot welding results in the formation of martensite, the hardness of which is dependent on the amount of C.

IV. Extra Deep Drawing High Strength Steel

The production of automobile components such as fenders and quarter panels requires Al-killed steel. In some special cases, certain components cannot be produced without employing decarburized/denitrogenized extra deep drawing steel. For these purposes, a high strength steel with better deep drawability than that of rephosphorized steel is required. In order to produce such an extra deep drawing high strength steel, the addition of solution hardening elements to an extra deep drawing mild steel is suggested, for example, an extra low C Ti-killed steel with an r-value larger than 2.0. However, when P is added to strengthen such a Ti-killed steel, the r-value deteriorates sharply (1.5~1.6). When Mn or Mn+Si is added for the same purpose, an r-value of approximately 1.8 can be obtained in this steel, the same as that of an ordinary rephosphorized steel.

Besides Ti, there are other carbonitride formers such as Nb, Zr, etc. Excessive addition of Nb (free Nb ≥ 0.025%) relative to the equivalent atomic ratio of C and N in extra low C steel produces a high r-value of over 2.0. However, the amount of P added must therefore be limited to approximately 0.1%, and is supplemented with Mn when a higher strength steel is desired.

A smaller addition of Nb was found capable of producing cold-rolled steels with a high r-value and improved elongation only if the preceding hot rolling was done under the proper conditions. Nb steels, hot-rolled, cold-rolled, continuously-annealed, and then temper-rolled, exhibited a greater elongation and a higher r-value, with a lower yield strength when the reduction during the hot rolling was high and when the number of passes was increased. These results are illustrated in Table 1. Based on these results, commercially produced slabs with different ratios of Nb/C were hot rolled using a 7-stand finishing mill, with a reduction of 92%. The hot-rolled steel sheets...
thus produced were then subjected to a cold rolling and continuous annealing process, the characteristics of which are as shown in Fig. 9. The $\tilde{f}$-value rises as the Nb/C ratio increases, but maintains a value of 2 or over even when the Nb/C ratio is 1 or less. On the other hand, the elongation increases greatly as the Tb/C ratio decreases.

Finer grains and larger precipitates are observed in hot-rolled sheet rolled in a tandem mill than that rolled in a laboratory mill, as shown in Photo. 1. The precipitates in the latter lie in rows, which means that precipitation occurred mainly during the $r \rightarrow a$ transformation and that insufficient precipitation occurred in the $r$ phase under the laboratory hot rolling conditions.

As described above, the free C or N, the grain and precipitate sizes, and the precipitate distribution are influenced by the hot rolling conditions, and accordingly the properties of cold-rolled and annealed sheet depend on the hot rolling conditions.

2. Influence of Solution Hardening Elements

With this steel as a base, solution hardening elements such as Mn, Si, and P were added and small ingots cast. These ingots were subjected to hot rolling under conditions $B$ in Table 1, followed by cold rolling and continuous annealing, giving the prop-

![Table 1. Effect of hot rolling conditions on tensile properties of 0.003%C-0.04%Nb-0.03%Al steel.](image-url)

* Cold reduced by 79%, annealed at 830°C for 40 s, and temper rolled by 0.8%.
** The difference between the flow stress after 7.5% prestraining and the yield stress after subsequent heating at 100°C for 30 min.
The yield strengths, tensile strengths, and elongations obtained can be expressed as a function of a parameter, $Mn + Si + 10P\%$, varying with changes in the amounts of the alloying elements. However, the $f$-value deteriorates the most in the case of Mn additions, then Si, and then P. Additionally, it must be noted that the deterioration in the $f$-value when Si or Mn is added together with 0.04%P is less than when just Si or Mn is added alone. The aging index gets larger with increasing amounts of the alloying elements P, Si, and Mn.

The relation between the $f$-value and the aging index is shown in Fig. 11 for P steels with 0.005%C and different amounts of Nb. In the steel with Nb/C = 3, the aging index is zero, even if the quantity of P increases, and the decrease in the $f$-value is smaller than in the steel with Nb/C = 1. It is well known that the existence of free C before annealing prevents the development of {111} texture during annealing. In this Nb-steel, containing a small amount of Nb, the precipitation of C or N may be restrained by the P during hot rolling, so that some free C or N may remain in the hot-rolled sheet. Thus for steel with a large Nb/C value, the $f$-value does not deteriorate so much as for steel with a small Nb/C value. Even a steel containing a smaller amount of Nb, if hot rolled under the proper conditions so that the precipitation of C or N is accelerated, may give an improved $f$-value, as shown in Fig. 10.

It has been reported<sup>6</sup> that for Ti-killed steel containing P the reason for the large deterioration in $f$-value is coarse Fe–Ti–P precipitates which prevent the development of {111} texture. However, in the steels containing a large amount of Nb, the deterioration in $f$-value was small when P was added. The reason may be that a precipitate containing Nb and P does not form or that it does not prevent the development of a {111} texture even if it does form.

As a result of this, in order to obtain a high strength steel with a high $f$-value, P is the most effective in the elements P, Si, and Mn as an alloying element. However, P segregates to the grain boundaries and makes steel brittle. Figure 12 shows the effects of the quantity of P and the cooling rate after annealing on brittle fracture in a steel containing 0.005%C and 0.04%Nb. Photograph 2<sup>11</sup> shows examples of collapsed conical cups which were tested to study the differences in brittleness. According to Fig. 12, when the cooling rate is large, even if the quantity of P is large, the steel does not crack. It is concluded that in the present Nb-containing steel, brittleness caused by P can be prevented by control of the quantity of P or the cooling rate.

Based on the above results, commercial production of extra deep drawing high strength steels ($f=2.1$, $EI=41\%$) has been realized by the tandem hot rolling of extra low C–Nb–P steel.

Because the affinity of Nb for S and O is weaker than that of Ti, and because N can be stabilized with Al, the amount of Nb necessary to stabilize the C is sufficient (equivalent to Nb and C, or less). Therefore, in contrast to the case of Ti additions, the for-
formation of inclusions that cause surface defects is less likely.

3. Hot Dip Galvanizing

Hot dip galvanizing cannot be applied to dual phase steel or rephosphorized steel, but the extra deep drawing high strength steel sheet has an additional advantage in that hot dip galvanizing can also be performed on it. The reasons why hot dip galvanizing cannot be applied to dual phase steels are that the large amounts of alloying elements cause deterioration of adhesion, and that the transformation of martensite to pearlite is accelerated by the slow cooling or soaking during galvanizing. Rephosphorized steel shows its non-aging properties and a high $r$-value only when it undergoes a slow heating and cooling cycle, as employed in the box annealing method. It therefore cannot exhibit the wanted properties when produced in-line continuous annealing and galvanizing. If an adequate amount of P that does not result in embrittlement, depending on the cooling rate following annealing, is added as a strengthening element, the extra deep drawing high strength steel would exhibit excellent adhesion of Zn in both galvanizing and galvannealing.

V. Properties of 40 kgf/mm² Class High Strength Cold-rolled Steel Sheets

The compositions of the 40 kgf/mm² class sheets; the above dual phase steel, $DP$, rephosphorized steel, $DDH$, and the extra deep drawing high strength steel, $EDDH$, together with their mechanical properties and those of Al-killed steel, $DDQ$, are shown in Tables 2 and 3 and Fig. 13.

1. Deep Drawability

The surprisingly high $r$-value of 2.15, and the fact that it had the lowest conical cup value (CCV in the Fukui test) and the highest bore expanding limit prove the excellent deep drawability of the high strength steel, $EDDH$. Comparison of the limit of the drawing capability ratio when drawn by a 33 mm diameter

<table>
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<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Cr</th>
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<td>$DDQ$</td>
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<td>0.025</td>
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<td>0.012</td>
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<td>0.50</td>
<td>0.084</td>
<td>0.009</td>
<td>0.049</td>
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<tr>
<td>$EDDH$</td>
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<td>0.074</td>
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<th>TS (kgf/mm²)</th>
<th>EI (%)</th>
<th>YR (%)</th>
<th>$\eta_{12}$</th>
<th>$\bar{t}$</th>
<th>CCV (mm)</th>
<th>LDR</th>
<th>Bulge height (mm)</th>
<th>Bore expanding limit (%)</th>
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<td>32.2</td>
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punch, indicated in Photo. 3, further shows the excellent drawability of EDDH. The rephosphorized steel, DDH, comes second, next to EDDH, in terms of good drawability.

2. Stretchability

The DP steel has the greatest bulge height and work hardening rate, n-value, which indicates its excellent stretchability. The EDDH has a large elongation and is next to the DP in its bulge height and n-value, and therefore also has good stretchability.

3. Shape Fixability

The relation between strain and n-value during tension testing is shown in Fig. 14. The DP steel has the lowest yield strength and a high n-value, particularly in the small strain region. This means that the spring back will be small for lightly drawn parts, and that the DP possesses excellent shape fixability. When compared to the DDH, the EDDH also has a low yield strength, a high n-value, and excellent shape fixability.

4. Dent Resistance

Steel sheets with a high strain hardening exponent, n-value, and a bake hardenability, BH, have excellent dent resistance, and can be utilized for lightly drawn parts. Since the DP has a very high n-value and BH, its shape fixability and dent resistance can be utilized to the full extent if it is used for flat shaped components such as the hood and trunk lid.

5. Grain Diameter

Photograph 4 shows the microstructures of four types of steel. It must be noted that when compared to the box-annealed DDQ and DDH, the continuously annealed DP and EDDH exhibit a much finer grain diameter. This is due to the partial transformation
of austenite into martensite and ferrite in the dual phase steel, $DP$, and the inhibition of grain growth due to the existence of fine $\text{Nb}$(C, N) precipitates in the Nb containing steel, $EDDH$.

VI. Conclusion

This paper has discussed the metallurgical factors involved in the production of three types of high strength cold-rolled steel sheets possessing good press formability, and their properties, focusing on 40 kgf/mm² tensile strength. The features of each type of steel are summarized as follows.

1. Dual Phase Steel

Dual phase steel consists of ferrite and martensite, the formation of which is the result of the addition of Mn and Cr as alloying elements and a rapid cooling following continuous annealing. The steel possesses a very low yield to tensile strength ratio, under 50%, and a high $n$-value. It possesses superior stretch formability, shape fixability, and bake hardenability, and is therefore suitable for use in lightly drawn, flat components because of its excellent dent resistance.

2. Rephosphorized Steel

Rephosphorized steel, a solution hardening steel, is produced mainly by adding P, with supplementary Mn, to box-annealed Al-killed steel, and has excellent drawability. The steel is suitable for use in drawing parts due to its high $f$-value of 1.5–1.8 and low yield to tensile strength ratio.

3. Extra Deep Drawing High Strength Steel

This steel is produced by the continuous annealing of extra low carbon Al-killed steel whose solute C is stabilized by an approximately equivalent amount of Nb, and to which P is added together with supplementary Si or Mn. Its deep drawability is better than that of rephosphorized steel, having an $f$-value of over 2.0, a high $n$-value, a low yield to tensile strength ratio, and a high elongation. Galvanized and galvannealed steel sheets can also be produced from this steel.

It is anticipated that these high strength steels will play a vital role in the creation of lighter and stronger automobile components.

REFERENCES