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Synopsis :
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Characteristics of Formable Cold Rolled High Strength Steel Sheets for Automotive Use*

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Metallurgical factors affecting the press formability of cold rolled high strength steels are discussed and the properties of 40 kgf/mm² class tensile strength steels are examined. Dual phase steel, CHLY, consisting of ferrite-martensite structure produced by rapid cooling in continuous annealing line has very low yield to tensile strength ratio and high n-value. Rephosphorized steel, CHR, is a batch annealed alminum killed steel hardened with phosphorus and manganese. It has high $\bar{r}$-value and relatively low yield strength. Recently developed steel, CHRX, with super deep drawing quality and high strength is characterized by its extremely high $\bar{r}$-value over 2.0 and low yield strength. It can be produced by continuous annealing of niobium-stabilized, extra low carbon, phosphorus-bearing steel. Spot weldability, formability and brittleness of the steels are also examined.

1 Introduction

Recently, much is being debated on the feasibility of high strength steel sheets in reducing weight and improving safety of automobile body. The biggest obstacle in using high strength steel sheets for auto body components is problems involving press formability. This report discusses three types of steels: dual phase steel, rephosphorized steel, and super deep drawing high strength steel, with emphasis on metallurgical characteristics of cold rolled high strength steel sheet possessing excellent press formability; the first two especially known for their wide acceptance, and the last for its recent development. Various metallurgical factors affecting the formability of these steels are also discussed.

2 Dual Phase Steel: CHLY

Yield strength (YS) is one of the major factors influencing the press formability of steels. For instance, the reason why decarburized and denitrogenized steel (KTS) produced through open coil annealing possesses a higher degree of formability than ordinary aluminum killed steel (SPCE) is not only because the former steel has a greater elongation (El) by 3–4%, but also because the former possesses a lower yield strength by 3–4 kg/mm² in comparison to the latter[1]. However, when solution hardening elements such as Mn and Si are added for the purpose of increasing tensile strength (TS), YS increases with 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, YR decreases to approximately 50%, and moreover, YS sharply increases due to strain aging[2]. This means that 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 increases after forming, coating, and baking. Austenite is present when a steel sheet is being annealed above A_1 temperature, and this austenite transformes into martensite during the stage of rapid cooling. As a result, this steel sheet exhibits dual phase structure, i.e. the martensite islands dispersed in the ferrite matrix. The strength of this steel sheet depends on the volume fraction of martensite. For example, 40 K steel (tensile strength of approximately 40 kg/mm²) is produced when the amount of martensite is 2–5%, whereas 100 K steel is obtained when the martensite is increased to several tens percent.

2.1 Low Yield Ratio

Nevertheless, the mere existence of martensite does not produce steel sheets of a low yield ratio and a large elongation. Austenite has a face centered structure, containing a large amount of carbon in solution. It transforms into ferrite and pearlite having a body

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centered structure when subjected to slow cooling. It, however, transforms into martensite of a body centered structure while maintaining a large amount of carbon when rapidly cooled.

Fig. 1[3] shows the relationship between the critical cooling rate (CR) which is the minimum requirement for forming dual phase structure and the amount of alloying elements. One specimen contained 0.05% C and 0.6–1.7% Mn. A 0.5% max. Cr or Mo was added to the other two specimens with 0.05%C and 1.2% Mn. The specimens were cold rolled and then subjected to a one minute heating at 770°C before being colled at 5–2 000°C/s.

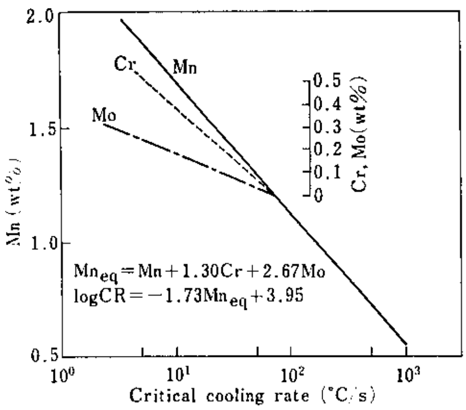

Fig. 1 Relationship between the critical cooling rate and the amount of alloying elements

CR must be increased with a decrease in the amount of the alloying element. For example, CR in a 0.6% Mn steel is one-hundred times that in a 1.7% Mn steel. The effect of Cr or Mo on the critical cooling rate is 1.3 or 2.7 times, respectively, that of Mn.

Fig. 2[4] shows the effects of cooling rate and alloying content on the equi-YR of 50% and equi-YS of 22 and 25 kg/mm² curves.

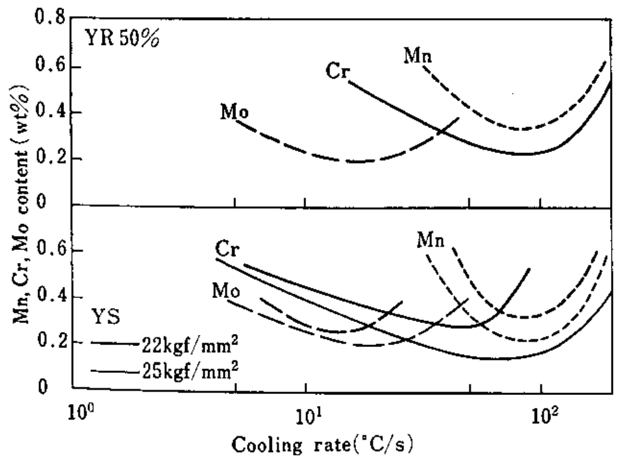

Fig. 2 Effect of cooling rate and amount of alloying elements on equi-YR curves and equi-YS curves (basic composition: 0.05% C–1.2% Mn)

In regard to steels to which Mn, Cr, and Mo were added, both the equi-yield to tensile strength ratio line and the equi-yield strength line form downward curved lines. These curves show that alloying elements must be increased in order to achieve lower YS and that each curve has an optimum cooling rate with the least amount of additives. Arranged in the order of slowness of the optimum cooling rate, Mo is the slowest, followed by Cr, and then by Mn. Nevertheless, whereas low yield strength is attainable from Cr over a wide range of cooling rates, the range narrows with Mn. Moreover, in the case of the Mn-added steels, it is necessary to keep cooling rate in the range of 50–100°C/s to obtain the YS lower than 25 kg/mm².

Minimum yield strength of 22 kg/mm² is obtainable from Mn- or Mo-added steels, but it is possible to get yield strength less than 20 kg/mm² in case of Cr-added steels. The reason for this is that, as shown in **Fig. 6**[4]. Solution hardenability of Cr is less than those of Mn or Mo[3,5].

2.2 High Ductility

Both dual phase steels and ferrite-pearlite steels were made from the same alloy by changing the cooling rate after annealing and then mechanical properties as annealed state were compared. YS, TS and El

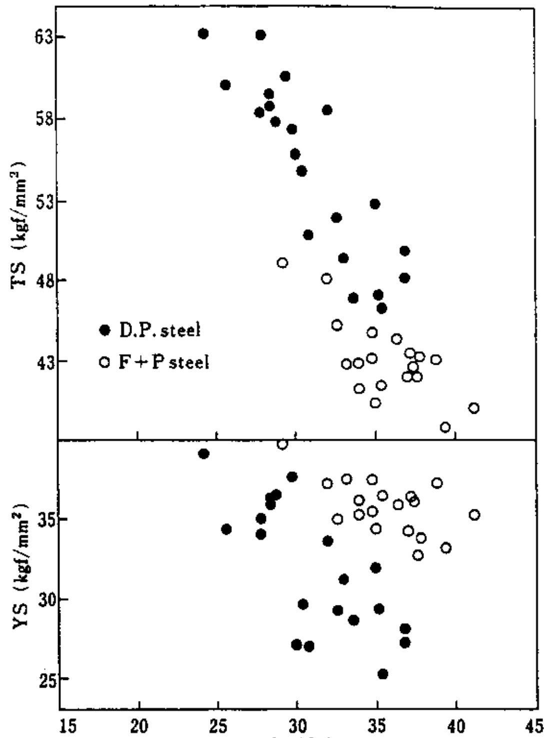

Fig. 3 Tensile properties of dual phase steel and ferrite-pearlite steel (continuous annealing at 770°C)

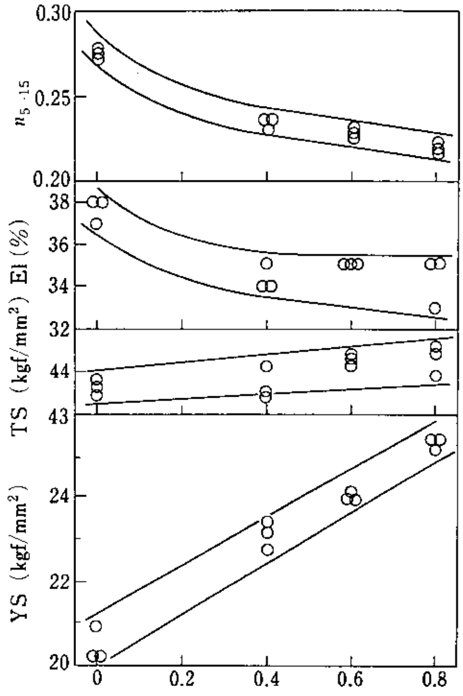

Fig. 4 Changes in tensile properties of dual phase steel caused by temper rolling

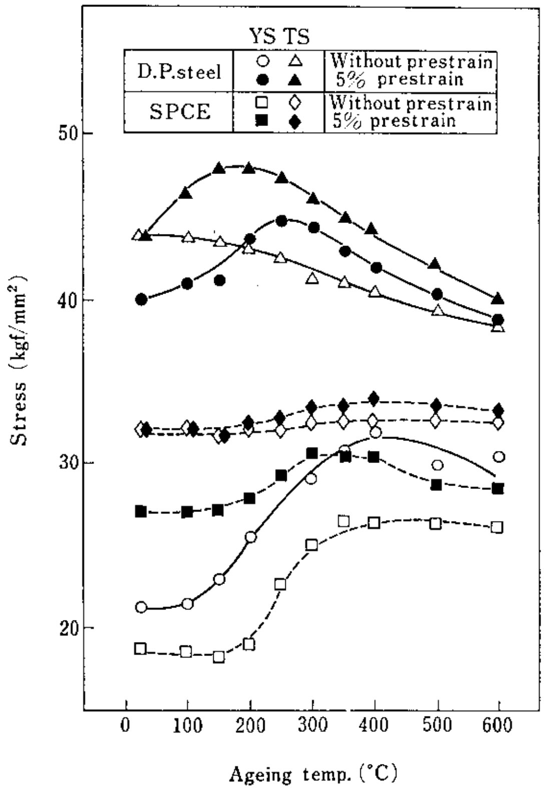

Fig. 5 Aging temperature dependence of tensile properties of dual phase steels age hardened for 20 min

in these steels are shown in **Fig. 3**. YS is obviously lower in DP steel than in F + P steel, however, El is somewhat higher at the same TS. Moreover, temper rolling must inevitably be performed on F + P steels after annealing in order to extinguish yield point elongation, whereas such treatment is unnecessary for DP steels. For example, **Fig. 4**[4)] illustrates changes in tensile properties when temper rolling was performed on DP steel in order to regulate the surface roughness and to readjust the flatness. Although TS hardly changes, YS, El, and the work hardening rate (*n*-value) deteriorate with an increase in reduction, and under the usual reduction rate of 0.8%, YS increases by approximately 4 kg/mm², while El and $n_{5\text{-}15}$ decrease by approximately 3% and 0.5, respectively.

In case of ferrite-pearlite steel, it is necessary to be temper-rolled after annealing, resulting in less elongation values than the ones shown in **Fig. 3**. The low yield to tensile strength ratio, high elongation, and high work hardening characteristics in small strain range are the special properties of DP steel, and the reason for its characteristics lies in the fact that cold working is not performed (or rather, cold working is unnecessary) on the steel after annealing.

2.3 Large Bake Hardenability

The strain aging properties of dual phase steel containing Cr, are compared with those of aluminum killed steel (SPCE) in **Fig. 5**[4)]. YS in SPCE increased by about 9 kg/mm² from 18 kg/mm² to 27 kg/mm² as a result of a 20-min aging at 170°C after 5% pre-straining. On the other hand, YS in DP steel increased by approximately 21 kg/mm², from 21 kg/mm² to 42 kg/mm², proving a good performance in dent resistance. If a high-temperature bake coating could be developed, YS would show further improvements by approximately 3 kg/mm.² Another advantage of DP steel is the improvement of TS by approximately 10% during the period of strain aging.

3 Rephosphorized Steel: CHR

Since the aforementioned DP steel possesses a low $\bar{r}$ value of 0.9–1.1, the steel is not suitable for deep drawing parts.

Whether in the case of the solution hardening method in which alloying elements are added, or in the case of the strengthening by transformation, a certain type of alloying element is added to steels to increase TS. However, these additives cause changes to El and YS. Obtained through regression analyses, **Fig. 6** shows the effect of strengthening elements generally used, such as C, Si, Mn, P, and Cr on TS, YS and El in steel sheets which were box annealed at

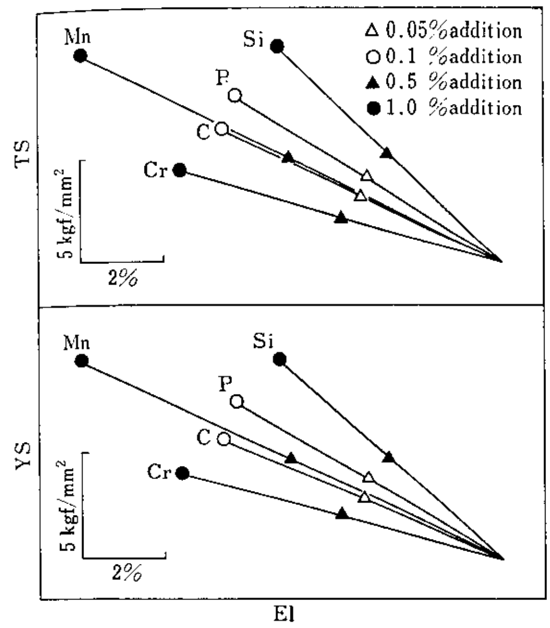

Fig. 6 Effect of alloying elements on tensile properties of cold rolled steel sheets (box annealed at 670°C for 10 hours, 0.8 mm in thickness)

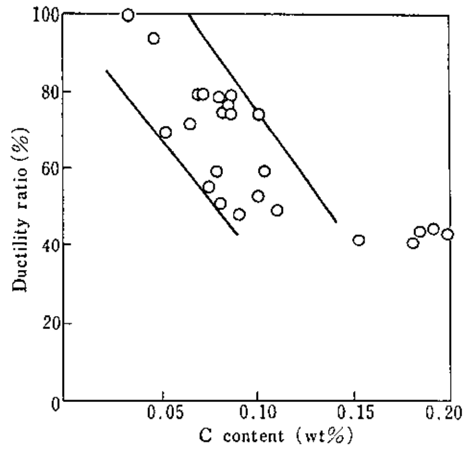

Fig. 7 Effect of C content on the ductility ratio of spot welds

670°C for 10 hours following cold rolling to a thickness of 0.8 mm. In **Fig. 6**, the increase in TS is accompanied by a decrease in El. In terms of a decrease of El to the same increase of TS, Si is the smallest, followed by P, Mn, and then C. These elements exhibit the same tendencies in regard to the relationship between YS and El. Increases in TS are in proportion to those in YS; therfore the ratio of YS to TS keeps almost constant. Among these elements, P is well known for its favorable effect of improving the texture of cold rolled steel sheets. Taking such advantage of P being only second to Si for its small decrease in El to the increase in TS, the high strength steel with high $\bar{r}$-value ($\bar{r}$ = 1.5–1.8), which is made by adding P to aluminum killed steel, is called rephosphorized steel. However, the increase in P content results in the embrittlement of steel sheets and deteriorates spot weldability. Therefore, for practical reasons, the amount of P to be added must be limited to approximately 0.1%, and Mn is further supplemented when higher strength steel is desired. Although Si is more favorable than Mn from the standpoint of elongation, Si is easy to oxidize and liable to generate temper color during box annealing. Additionally, even though C is the least expensive among these strengthening elements, the ductility ratio (cross tension strength/tesnile shear strength) following spot welding decreases to 50% or lower when the content of C exceeds 0.10%, as is shown in **Fig. 7**[6]. More than likely, the 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.

4 Super Deep Drawing High Strength Steel: CHRX

Production of automotive components such as fender and quarter panels requires aluminum killed steel. In special cases, certain components cannot be produced without employing decarburized/denitrogenized super deep drawing steel. For these purposes, high strength steel with better deep drawability than in rephosphorized steel is required.

A sufficient amount of carbonitride former necessary to completely stabilize the carbon and nitrogen in the steel, for example, Ti, is added to extra low carbon steel (creating the so-called Ti killed steel). It is known that this Ti killed steel possesses a super deep drawability with a $\bar{r}$-value of over 2.0[7]. However, when P is added in order to strengthen this steel, the $\bar{r}$-value sharply deteriorates (1.5–1.6)[8]. When Mn or Mn + Si is added for the same purpose, approximately 1.8 of the $\bar{r}$-value can be obtained, same as that of rephosphorized steel[8]. Moreover, because Ti has strong affinity with N, S, and O, an excessive amount of Ti must be added to completely stabilize the carbon, and these excesses produce numerous non-metallic inclusions which tend to make slivers.

4.1 Effect of Hot Rolling Conditions on Extra Low Carbon Nb Steel

Besides Ti, there are such carbonitride formers as Nb, Zr, etc. Excessive addition of Nb (free Nb ≥ 0.025%) in comparison to equivalent atomic ratio of C and N in extra low carbon steel produced a high $\bar{r}$-value of over 2.0, but its elongation was 48% or lower[9,10]. However, a smaller addition of Nb was

Table 1 Effect of hot rolling conditions on tensile properties of 0.005 C%–0.04% Nb–0.03% Al steel

	Hot rolling conditions			Tensile characteristics of cold roll sheet*				
	Number of pass	Total reduction(%)	Finishing tempra-ture(°C)	YS (kg/mm^2)	TS (kg/mm^2)	El (%)	$\bar{r}$	Al (kg/mm^2)
A	2	60	950	22	34	45	1.6	0
B	3	87	940	20	33	48	1.9	0

*Cold reduced by 79%, annealed at 830°C for 40 sec. and temper

found capable of producing cold rolled steels with high $\bar{r}$-value and improved elongation only if the preceding hot rolling was, made under proper conditions. Nb steel, hot rolled, cold rolled, continuously annealed and then temper rolled, exhibited a greater elongation and $\bar{r}$-value, with lower yield strength when reduction during the hot rolling was high and when the number of passes increased. The above results are illustrated in **Table 1**[4]. Based on these results, commercially produced slabs with different ratios of Nb/C were hot rolled with a 7-stand finishing mill in 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. 8**[4]. The $\bar{r}$-value, although rises as the Nb/C ratio increases, maintains the value of 2 or over even if Nb/C becomes 1 or under. On the other hand, elongation increases greatly as Nb/C decreases. This steel sheet possesses the same excellent deep drawing properties when batch annealed, and the sheet is marketed as a super deep drawing cold rolled steel sheet, KTUX.

4.2 Influence of Solution Hardening Elements

With this steel as the base, such solution hardening elements as Mn, Si, and P were added to make small ingots. These ingots were subjected to hot rolling, cold rolling, and continuous annealing, with their

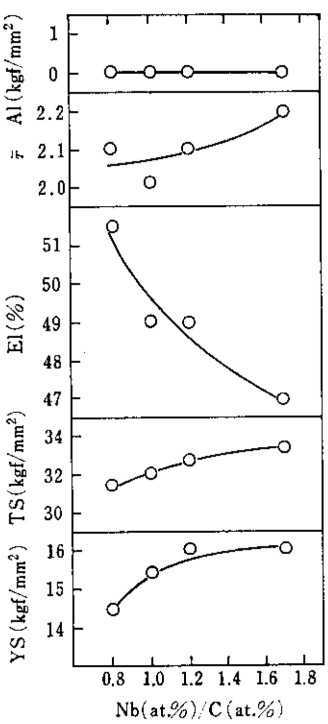

Fig. 8 Effect of Nb/C atomic ratio on tensile properties of Nb bearing extra low carbon cold rolled steel sheets hot rolled by a tandem mill

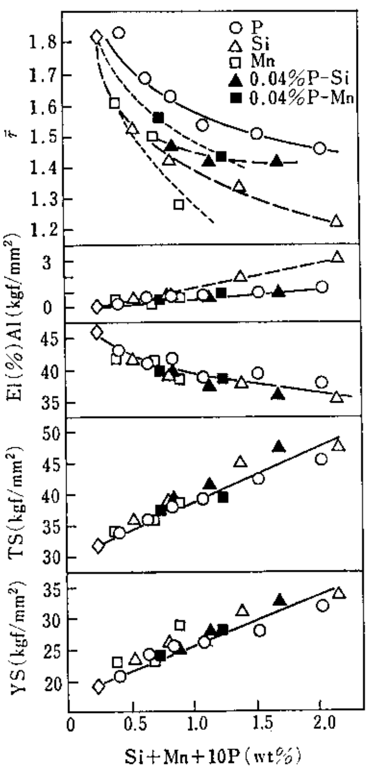

Fig. 9 Effect of alloying elements on tensile properties of Nb bearing extra low carbon cold rolled steel sheets

properties shown in **Fig. 9**[11]. Yield strength, tensile strength, and elongation can be expressed as a function of a parameter, Mn + Si + 10P(%), while they vary according to changes in amounts of alloying element. However, the $\bar{r}$-value deteriorates then by greatest in the case of Mn, followed by Si, and P. Additionally, it must be noted that deterioration of the $\bar{r}$-value when Si or Mn is added together with 0.04 P is lesser than in the case of the single addition of Si or Mn.

Based on the above results, commercial production of super deep drawing high strength steels ($\bar{r}$ = 2.1, El = 41 %) has been realized through the tandem hot rolling of extra low carbon-niobium steel with P addition.

An anticipated post-deep drawing embrittlement of a P-bearing extra low carbon steel due to segregation of P at the grain boundaries can be prevented by increasing the cooling rate after continuous annealing. **Photo. 1** shows the results of a low temperature collapsing test performed after drawing, and as seen from the results, no ruptures were noticed in material subjected to rapid cooling at a rate of 20°C/s. This implies that this steel cannot be manufactured by the box annealing method which has a slow cooling rate.

Because the affinity of Nb with S and O is weaker than Ti, and because N can be stabilized with Al, only the amount of Nb necessary to stabilize C is sufficient (equivalent to Nb and C, or thereunder). Therefore, unlike the case of Ti, formation of inclusions which cause surface defect is less likely to occur.

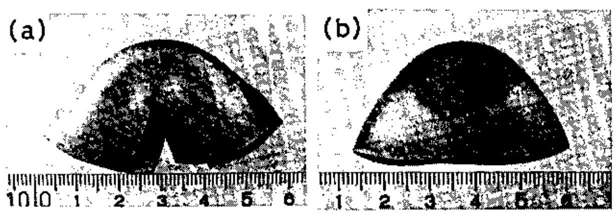

Photo. 1 Collapsed conical cups of CHRX steel sheet containing 0.07% P (0.8 mm thick, tested at 0°C): cooling rate after annealing at 830°C; (a) 1°C/s, (b) 20°C/s

4.3 Hot Dip Galvanizing

Electrogalvanizing can be applied to dual phase steel CHLY, rephosphorised steel CHR, as well as to CHRX, but the super deep drawing high strength steel sheet, CHRX, has an additional advantage in that the application of hot dip galvanizing can also be performed. The reasons why hot dip galvanizing cannot be applied to dual phase steels are because the numerous alloying elements deteriorate adhesion, and because transformation of martensite to pearlite is accelerated at the heating process for the galvannealing. Rephosphorized steel will show its non-aging property and a high $\bar{r}$-value only when it undergoes a slow heating and cooling cycle employed in the box annealing method. Therefore, it cannot exhibit the expected properties with the galvanizing line of in-line continuous annealing. If the adequate amount of P which will not result in embrittlement depending on the cooling rate following annealing is added as strengthening element, and if a supplementary amount of Mn is added to meet the required strength of the steel, CHRX would possess excellent adhesion in both galvanizing and galvannealing.

5 Properties of 40 kg/mm² Class High Strength Cold Rolled Steel Sheets

The compositions of the 40 kg/mm² class, aforementioned dual phase steel, CHLY, rephosphorized steel, CHR, and super deep drawing high strength steel, CHRX, as well as their mechanical properties with those of aluminum killed steel, SPCE, are shown in **Tables 2** and **3**, and **Fig. 10**.

5.1 Deep Drawability

The surprisingly high $\bar{r}$-value of 2.15, 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, CHRX. The

Table 2 Chemical composition of cold rolled products

(wt%)

Steel		C	Si	Mn	P	S	Al	Cr	Nb
SPCE,	Al-killed	0.047	0.025	0.30	0.012	0.012	0.069	—	—
CHLY,*	dual phase	0.034	0.034	1.21	0.014	0.008	0.044	0.47	—
CHR,*	rephosphorized	0.051	0.022	0.50	0.084	0.009	0.049	—	—
CHRX,*	extra low carbon, rephosphorized	0.005	0.24	0.14	0.074	0.008	0.042	—	0.04

* CHLY : Cold rolled High tensile and Low Yield strength steel
CHR : Cold rolled High tensile strength Rephosphorized steel
CHRX : Cold rolled High tensile strength Rephosphorized extra deep drawing steel

Table 3 Mechanical properties of products (0.8 mm thick)

	YS (kgf/mm^2)	TS (kgf/mm^2)	El (%)	YR (%)	n_{5-12}	$\bar{r}$	CCV (mm)	LDR	Bulge hegiht (mm)	Bore expanding limit (%)	Annealing
SPCE	18.3	32.2	46	57	0.24	1.70	37.40	2.09	55.4	107	Box
CHLY	19.9	43.8	39	45	0.28	1.04	38.75	2.06	55.4	70	CAL
CHR	23.0	40.1	39	58	0.24	1.78	37.60	2.15	50.1	99	Box
CHRX	22.0	39.2	41	54	0.26	2.15	36.97	2.24	53.2	144	CAL

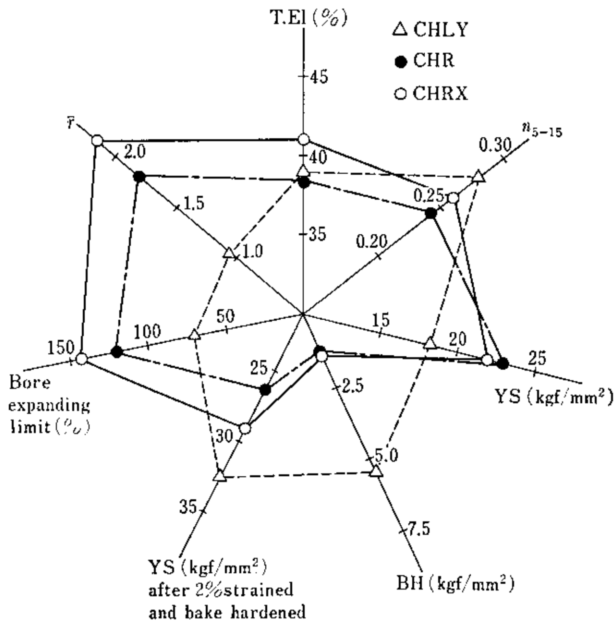

Fig. 10 Comparison of mechanical properties of steel sheets indicated in Tables 2 and 3

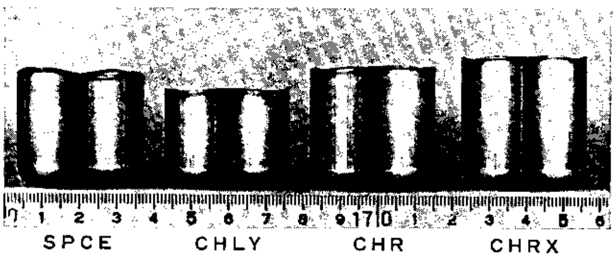

Photo. 2 Deepest cups drawn by 33 mm diameter punch in the LDR test

limit of the drawing capabilities ratio when drawn by a 33 mm diameter punch indicated in **Photo. 2.** further proves the excellent drawability of CHRX, The rephosphorized steel, CHR, comes second, next to CHRX, in terms of good drawability.

5.2 Stretchability

CHLY has the greatest bulge height and strain-hardening exponent, n-value, which indicate its excellent stretchability. CHRX has high elongation and is next to CHLY in its large bulge height and n-value, and therefore, it also has good stretchability.

5.3 Shape Fixability

The relation between strain and n-value in the tension test is shown in **Fig. 11**. CHLY has the lowest yield strength and a high n-value, particularly at the small strain region. This means that the spring back is small at slightly drawn parts, and that CHLY possesses excellent shape fixability[2]. In comparison to CHR, CHRX also has a low yield strength, a high n-value, and excellent shape fixability.

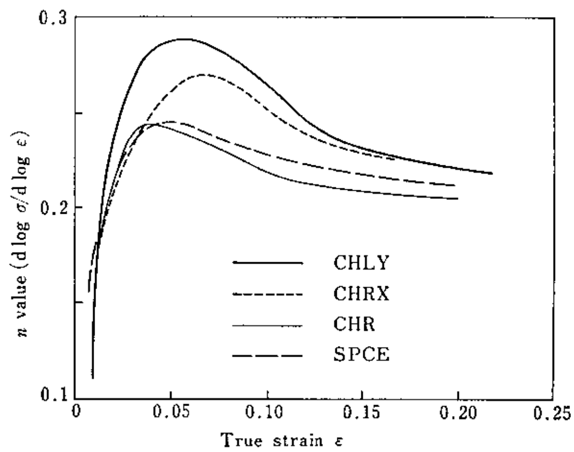

Fig. 11 Relation between n-value and strain of steel sheets shown in Tables 2 and 3

5.4 Dent Resistance

Steel sheets with a high strain hardening exponent, n-value, and a bake hardenability, ΔBH, show excellent dent resistance, and they can be utilized for slightly drawn parts. Since CHLY has a very high n-value and ΔBH, its shape fixability and dent resistance can be demonstrated to the full extent[2] if CHLY is utilized for flat shaped components such as hood and trunklid.

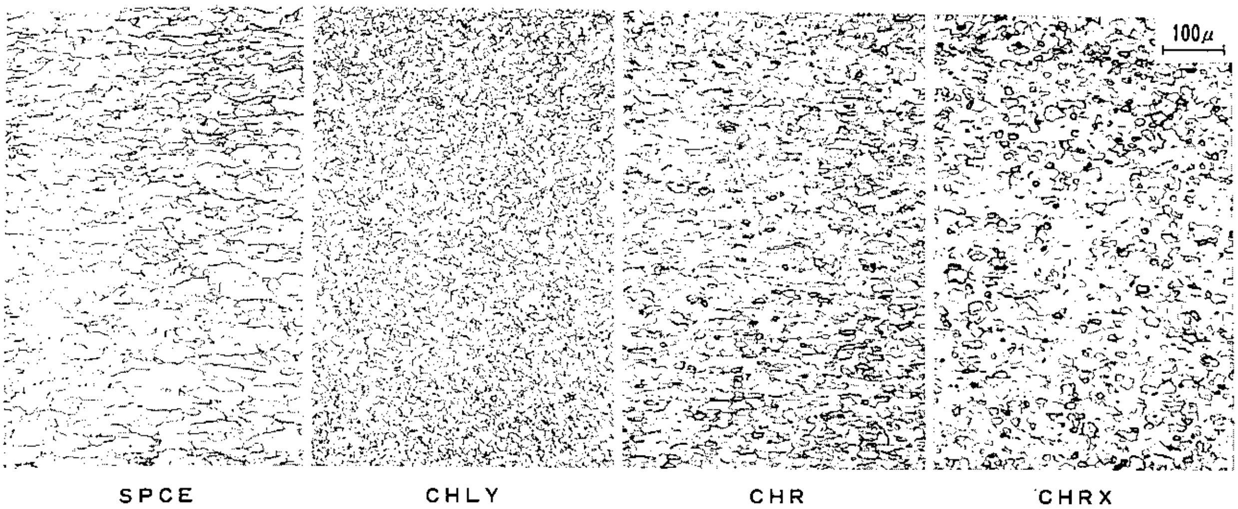

Photo. 3 Microstructure of cold rolled steel sheets shown in Tables 2 and 3

5.5 Grain Diameter

Photo. 3 shows the microstructures of four types of steel. It must be noted that when compared to the box annealed SPCE and CHR, continuously annealed CHLY and CHRX exhibit a much finer grain diameter. This is due to the partial transformation of austenite into martensite and ferrite in dual phase steel, CHLY, and the inhibition of grain growth due to the existence of fine Nb(C, N) precipitates in the Nb bearing steel, CHRX.

5.6 Spot Weldability

Spot welding conditions for four types of steel are listed in **Tables 2** and **3** (relations among the electrode force, welding current, and weld strength are

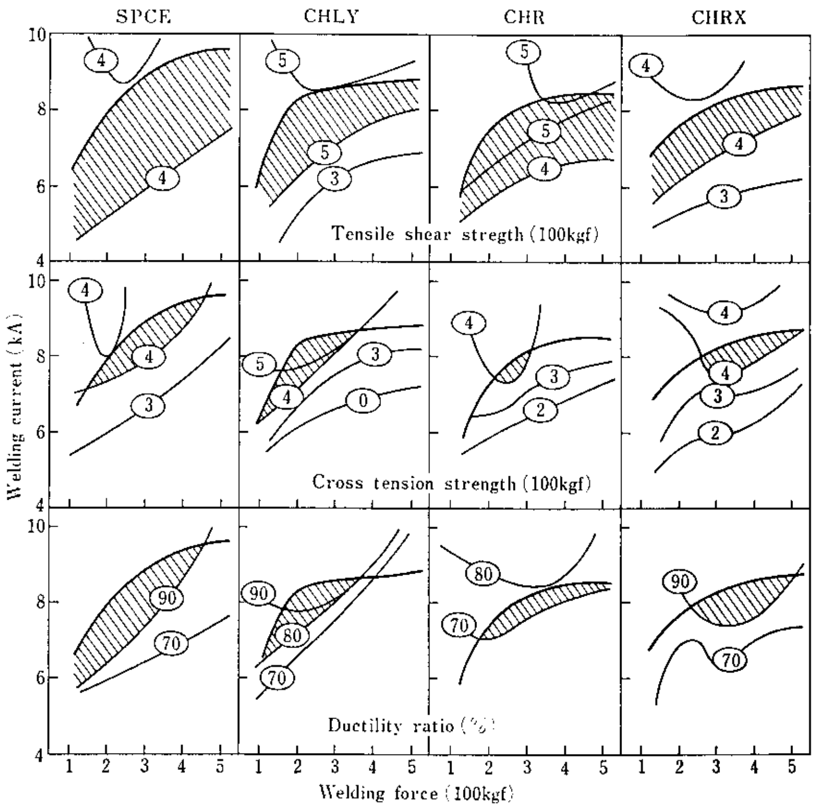

Fig. 12 Effect of electrode force and welding current on the strength in spot welded joints of steel sheets shown in Table 3 (The thick line indicates the critical welding current for nonexpulsion welds, and the area with oblique lines indicates the optimum welding conditions)

shown in **Fig. 12**). When electrode force is fixed at a certain point, the critical welding current for non-expulsion welds of high strength steels shows a shift to the side of lower current in comparison to that of the mild steel sheet, SPCE. The range where the ductility ratio (cross tension strength/tensile shear strength) exceeds 90 %, is widest among mild steels, followed by CHRX. The reason for this is due to the extra low C content, in spite of the high P content. Nevertheless, it is possible to spot weld high strength steels under almost the same welding conditions as for mild steels and achieve similar results regarding strength.

6 High Yield Strength Steel: APFC

Besides the recently developed, aforementioned three types of high strength cold rolled steel sheets for automotive use, there is also a high yield strength steel, APFC. This steel is produced through adding the solution strengthening elements, mainly Mn and Si, to the aluminum killed steel. The lowest limit for elongation and yield strength of the steel is standardized in JASO-M108 (Japan Automobile Manufacturer's Association's Specification). In comparison with the aforementioned three types of steel, the yield to tensile strength ratio of this steel is higher. Therefore this steel is suitable for slightly drawn or bent parts, but most portions of which do not suffer work hardening. The 50–60 kg/mm² classes are used most frequently, and the 60 kg/mm² class employs precipitation hardening and grain refining hardening effects of Ti and Nb in addition to solution strengthening.

7 Conclusion

This paper has discussed the metallurgical factors and the properties concerning the production of three types of high strength cold rolled steel sheets possessing excellent press formability, the focus of which was placed on the 40 kg/mm² in tensile strength. Features of each type of steel are summarized as follows:

(1) Dual phase steel: CHLY
This dual phase steel consists of ferrite and martensite, the formation of which is the result of the rapid cooling process following continuous annealing. The steel possesses a very low yield to tensile strength ratio and a high *n*-value. It possesses superior stretch formability, shape fixability, and bake hardenability; therefore it is suitable for use as slightly drawn, flat components, because of excellent dent resistance. Achieving a wide strength range of 40–100 kg/mm² classes by changing the volume fraction of martensite content is possible.

(2) Rephosphorized steel: CHR
CHR, a solution hardening steel, produced mainly by adding P, with a supplementary Mn to the box annealed aluminum killed steel with excellent drawability. The steel is suitable for use as drawing parts due to its high $\bar{r}$-value of 1.5–1.8 and low yield to tensile strength ratio.

(3) Super deep drawing high strength steel: CHRX
CHRX is produced by the continuous annealing of extra low carbon aluminum killed steel whose solute C is stabilized by approximately equivalent amount of Nb, and to which P is added and Si or Mn is added supplementarily. Its deep drawability is more excellent compared to rephosphorized steel in terms of $\bar{r}$-value of over 2.0, high *n*-value, yield to tensile strength ratio, and elongation. Galvanized and galvannealed steel sheets can also be produced.

Spot welded joints with high strength and high ductility ratio can be obtained with all of these high strength steel sheets by decreasing the welding current slightly in comparison to mild steels.

It is greatly anticipated that these high strength steels will play avital role in the creation of lighter and stronger automotive components.

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