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Synopsis :

For the purpose of producing a highly formable dual phase steel by intercritical annealing, the effects of alloying elements and cooling rates on microstructure and properties have been studied. The effect of alloying elements on the critical cooling rate (CR) required for the formation of dual phase structure are representable equivalent manganese content (M<sub>neq</sub>):  $\log CR(^\circ\text{C}/\text{s}) = -1.73M_{\text{neq}}(\%) + 3.95$  Where  $M_{\text{neq}}(\%) = \text{Mn}(\%) + 2.67\text{Mo}(\%) + 1.3\text{Cr}(\%)$  When gas-cooled, a 1.2% Mn-0.5%Cr steel exhibits a low yield strength of 20kg/mm<sup>2</sup> and a low yield-to-tensile strength ratio as low as 0.4. Without causing solid solution hardening and a decrease in dissolved C content in ferrite, Cr reduces the yield strength of ferrite, resulting in the lowering of the yield strength of dual phase structure.

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<p><b>The body can be viewed from the next page.</b></p>
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# Effects of Alloying Elements and Cooling Rate after Annealing on Mechanical Properties of Dual Phase Sheet Steel\*

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*For the purpose of producing a highly formable dual phase steel by intercritical annealing, the effects of alloying elements and cooling rates on microstructure and properties have been studied.*

*The effect of alloying elements on the critical cooling rate (CR) required for the formation of dual phase structure are representable equivalent manganese content ( $Mn_{eq}$ ):*

$$\log CR (^{\circ}C/s) = -1.73Mn_{eq}(\%) + 3.95$$

$$\text{Where } Mn_{eq}(\%) = Mn(\%) + 2.67 Mo(\%) + 1.3 Cr(\%)$$

*When gas-cooled, a 1.2%Mn-0.5%Cr steel exhibits a low yield strength of 20kg/mm<sup>2</sup> and a low yield-to-tensile strength ratio as low as 0.4. Without causing solid solution hardening and a decrease in dissolved C content in ferrite, Cr reduces the yield strength of ferrite, resulting in the lowering of the yield strength of dual phase structure.*

## 1 Introduction

The desire to develop a safe automobile has led to intensified study of the adoption of high strength sheet steel to improve body strength, save fuel and minimize the extra body weight caused by the exhaust control devices now being installed in compliance with the Exhaust Gas Control Regulations. High strength sheet steel for this purpose must have not only high strength but also excellent formability. Various strengthening methods have therefore been tried in an attempt to gain maximum strength with minimum loss of ductility in the manufacturing process of high strength sheet steel. The methods tested include solid solution hardening, grain refining hardening and precipitation hardening.

Recently, it has been determined that both strength and ductility of high strength sheet steel can be improved by using a dual phase structure consisting of ferrite and martensite. Examples of such dual phase steel are the cold rolled steels described by N. Ohashi<sup>1)</sup>, S. Hayami<sup>2)</sup>, K. Nakaoka<sup>3)</sup> and the hot rolled steels described by K. Hashiguchi<sup>4)</sup>, M. Taka-

hashi<sup>5)</sup>, M.S. Rashid<sup>6)</sup> and J.H. Bucher<sup>7)</sup>.

Both cold rolled and hot rolled dual phase sheet steels have the following features:

- (1) Absence of yield point elongation,
- (2) Low yield and high tensile strengths, i.e., low yield-to-tensile strength ratio,
- (3) High ductility and high work hardening rate,
- (4) Large bake-hardenability,
- (5) Non-ageing at room temperature.

The most general manufacturing method of dual phase steel is continuous annealing method in which sheet steel is heated to  $\alpha - \gamma$  range (intercritical temperature) to obtain  $\alpha - \gamma$  phase and is subsequently cooled so that some fraction of  $\gamma$  phase transforms to martensite. The properties of the sheet steel manufactured by this method are influenced by heat treating condition and in particular by cooling condition. The cooling rate required for the formation of the dual phase depends on the stability of the  $\gamma$  phase formed during heating, i.e., chemical composition and heating temperature and time. In general, the cooling rate must be increased with decrease in the stability of  $\gamma$  phase.

For steel with a given chemical composition, there is the minimum cooling rate (the critical cooling rate) required for obtaining dual phase structure. This

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critical cooling rate can be predicted from CCT curve during cooling from  $\alpha-\gamma$  range. The authors calculated the CCT curves for steels with various chemical compositions and investigated the relationship between the alloy content and the critical cooling rate. The authors also conducted experiments on various kinds of steel to confirm the calculated relation between alloy content and the critical cooling rate and to examine the influence of these factors on tensile properties.

## 2 Relation Between Alloy Content and Cooling Rate Required For the Formation of Dual Phase

The relation between the critical cooling rate and the alloy content can be predicted from the CCT curve after heating steel in  $\alpha-\gamma$  range. However, it is difficult to experimentally obtain the CCT curves of various kinds of steel. The authors calculated the CCT curves after heating steel in  $\alpha-\gamma$  range and the amount transformed according to the method<sup>8)</sup> adopted by Y. Ito, et al. and where by the relationship between the critical cooling rate and the alloy contents was obtained.

### 2.1 Calculation Method

TTT curve can be calculated from the chemical composition and  $\gamma$  grain size using the result of regression analysis. Then CCT curve is derived from the TTT curve by calculating the incubation time of transformation and the amount transformed during step cooling, where continuous cooling is approximated by step cooling.

### 2.2 Influence of Alloying Element and Cooling Rate on the Formation of Dual Phase Structure

As shown in Fig. 1, heating temperature is chosen to

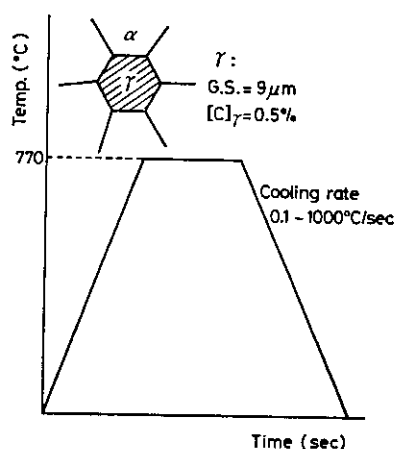


Fig. 1 Heat cycle used in calculation of CCT curve

be 770 °C in  $\alpha-\gamma$  range at which the fraction of  $\gamma$  phase is about 25 %, and the cooling rate is changed in the range of 0.1–1 000 °C/s (taking the experiment described later into consideration). The decomposition of  $\gamma$  phase during cooling is calculated on the assumption that C content in  $\gamma$  grain is 0.5 % and  $\gamma$  grain size is about 9  $\mu$ m. The Mn content is changed in the range of 0.3–3.0 %, and the other alloying elements, Mo, Cr, Si, Cu, and Ni, are changed where keeping Mn content at 1.2 %.

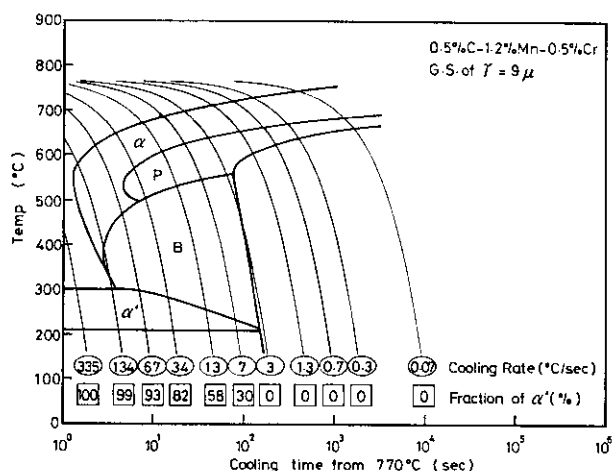


Fig. 2 Calculated CCT curve for 1.2% Mn-0.5% Cr steel ( $\alpha$ : ferrite, P: pearlite, B: bainite,  $\alpha'$ : martensite)

Fig. 2 shows the CCT curve of 1.2 %Mn-0.5 %Cr steel as an example of the calculation. It is clearly seen from this curve that the whole  $\gamma$  phase formed during heating transforms to martensite (hereinafter abbreviated as  $\alpha'$ ) at the cooling rate larger than about 200 °C/s. When the cooling rate is less than 200 °C/s, a part of  $\gamma$  phase changes to ferrite, pearlite, and bainite (hereinafter abbreviated as  $\alpha$ , P and B) during cooling, so the final fraction of  $\alpha'$  phase decreases. When the cooling rate is less than 7–3 °C/s, the decomposition of  $\gamma$  phase is completed in the high temperature range, and  $\alpha'$  phase cannot be obtained. That is, in 1.2 %Mn-0.5 %Cr steel the critical cooling rate required for obtaining dual phase is about 7–3 °C/s. The critical cooling rate obtained by this calculation is in good agreement with the experimental result.<sup>1)</sup>

Fig. 3 shows the relation between cooling rate and fraction of  $\alpha'$  in cooled condition. The critical cooling rate decreases with increasing contents of Mn, Cr and Mo. In 1.2 %Mo-0.5 %Cr steel, the fraction of  $\alpha'$  phase produced by the critical cooling rate of 5 °C/s is considered to be the minimum amount required for the formation of dual phase steel<sup>1)</sup>. In other alloy systems too, the cooling rate required for obtaining this critical fraction of  $\alpha'$  phase is regarded as the critical

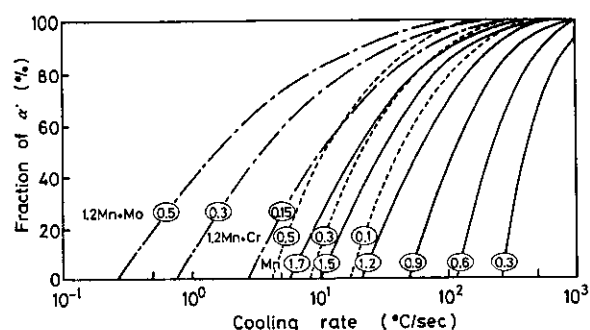


Fig. 3 Calculated relation between cooling rate and fraction of martensite in prior  $\gamma$  (the number in circle denotes the wt% of alloying elements)

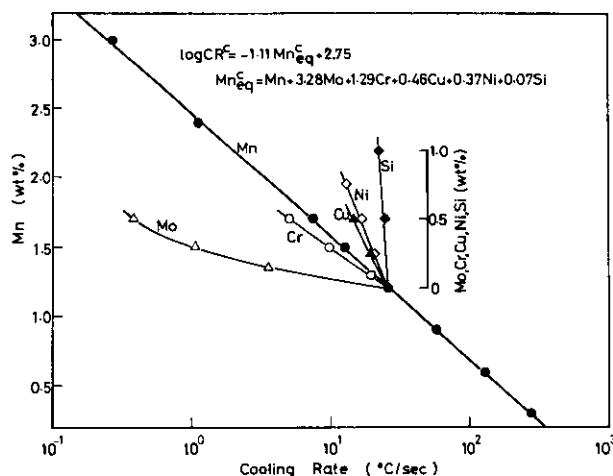


Fig. 4 Calculated relation between critical cooling rate and alloy contents

rate. Fig. 4 shows the relation between the critical cooling rate and alloy content. As clearly seen in this figure, logarithm of the critical cooling rate decreases in a linear manner with increasing alloy content. The influence of each alloying element on the critical cooling rate is converted into Mn content from curves in this figure and whereby "Mn equivalent ( $Mn_{eq}^C$ )" is obtained, given by equation (1). From this result, the relationship between the critical cooling rate  $CR^C$  and  $Mn_{eq}^C$  is obtained, given by equation (2).

$$Mn_{eq}^C(\%) = Mn(\%) + 3.28Mo(\%) + 1.29Cr(\%) + 0.46Cu(\%) + 0.37Ni(\%) + 0.07Si(\%) \quad (1)$$

$$\log CR^C(^{\circ}C/s) = -1.11Mn_{eq}^C(\%) + 2.75 \quad (2)$$

The effect of Mo on the critical cooling rate is the largest followed by Cr, Mn, Cu, Ni and Si.

### 3 Effects of Alloying Elements and Cooling Rate on Tensile Properties of Dual Phase Sheet Steel

The equations defining relations between alloy contents and the critical cooling rate above-mentioned were confirmed experimentally. The effects of these factors on tensile properties of dual phase sheet steel were studied.

#### 3.1 Materials and Experimental Procedure

The steels used in this experiment were vacuum-melted in a 50 kg high frequency furnace whose chemical compositions are shown in Table 1. Manganese content was varied over the range of 0.6 to 1.7 %, while chromium and molybdenum contents were varied in the range of 0 to 0.5 % and 0 to 0.3 %, respectively, in a basic 1.2 % Mn steel. The 50 kg ingots were hot-rolled to 2.5 mm thickness, normalized for 10 min. at 950 °C, pickled and subsequently cold-rolled to 0.8 mm thick sheets. Sheet specimens were heat treated using a direct resistance-heating furnace. The specimens were heated to 770 °C, held for 60 sec. followed by gas jet cooling, mist cooling or water quenching. The cooling rates were in the range of 5 ~ 50 °C/s, 100 ~ 200 °C/s and ~ 1 800 °C/s for gas jet cooling, mist cooling and water quenching, respectively.

Tensile specimens with gage sections 12 mm wide by 25 mm long were machined from heat-treated

Table 1 Chemical compositions of steels used

Steel	(wt%)								
	C	Si	Mn	P	S	Al	N	Cr	Mo
0.6Mn	0.053	0.012	0.62	0.004	0.002	0.038	0.0015	—	—
0.9Mn	0.050	0.013	0.92	0.003	0.001	0.033	0.0017	—	—
1.2Mn	0.050	0.013	1.20	0.003	0.001	0.033	0.0017	—	—
1.5Mn	0.048	0.011	1.52	0.004	0.001	0.033	0.0015	—	—
1.7Mn	0.048	0.011	1.70	0.004	0.001	0.033	0.0015	—	—
1.2Mn-0.1Cr	0.062	0.008	1.22	0.004	0.001	0.030	0.0014	0.10	—
1.2Mn-0.3Cr	0.062	0.008	1.22	0.004	0.001	0.030	0.0014	0.29	—
1.2Mn-0.5Cr	0.047	0.022	1.19	0.003	0.002	0.029	0.0017	0.49	—
1.2Mn-0.15Mo	0.054	0.011	1.22	0.004	0.001	0.030	0.0014	—	0.14
1.2Mn-0.3Mo	0.054	0.011	1.22	0.004	0.001	0.030	0.0014	—	0.30

materials. Tensile testing was performed in the as-annealed and aged (170 °C for 20 min.) conditions. Yield strength was determined either by the lower yield point or by 0.5 % offset stress in continuously yielded material. Ageing was performed to examine the degree of excessive interstitial C concentration and the consequent necessity for tempering after annealing.

### 3.2 The Effect of Alloy Content and Cooling Rate on the Tensile Properties in the Dual Phase Sheet Steel

The effect of cooling rate on the tensile properties of Cr-added steels is shown in Fig. 5. The tensile strength increases and the total elongation decreases monotonically with increasing cooling rate. The minimum cooling rate (thereafter called the critical cooling rate) at which the yield point elongation diminishes to zero, decreases with increasing Cr content. At the critical rate both the yield strength and the yield-to-tensile strength ratio (thereafter abbreviated as yield ratio) diminish. At any cooling rate both the yield strength and the yield ratio decrease with increasing Cr content. At higher cooling rates, the yield strength increases in a linear manner with cooling rate. Photo. 1 shows optical micrographs of specimens subjected to various cooling rates. When the cooling rate is less than a critical value, the microstructure consists of ferrite and pearlite. When the cooling rate exceeds a critical value, the microstructure consists of ferrite grains dispersed with fine martensite islands, regardless of cooling rate. The ferrite-pearlite structure exhibits yield point elongation, a relatively high yield strength and a large yield ratio, whereas the ferrite plus marten-

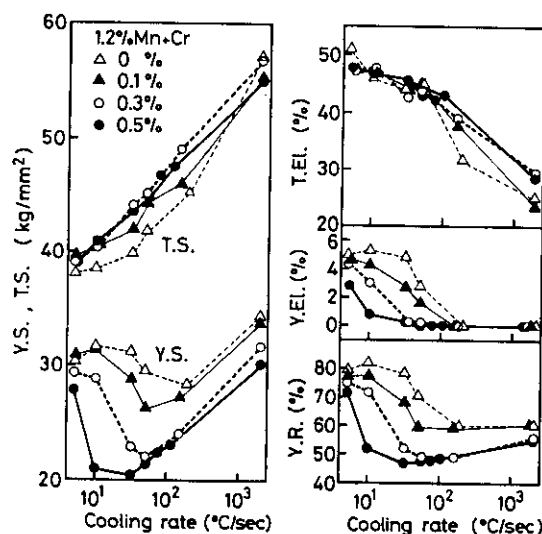


Fig. 5 Effect of cooling rate on yield and tensile strengths, yield-to-tensile strength ratio, yield point elongation and total elongation in Cr-bearing steels

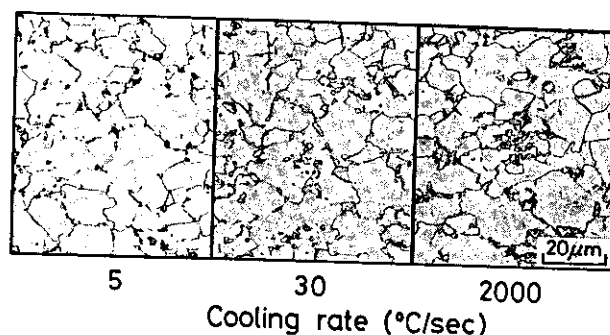


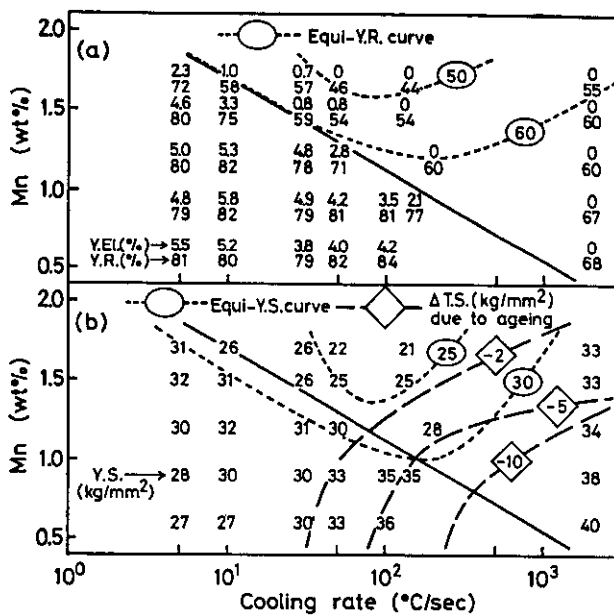
Photo. 1 Effect of cooling rate on microstructure of 1.2% Mn-0.5% Cr steel, exhibiting change in structure from ferrite-pearlite to dual phase

site duplex structure exhibits continuous yielding, a lower yield strength and a lower yield ratio, with a very good correspondence between microstructure and tensile behavior.

A similar behavior is found for the Mn- or Mo-added steels: With an increase in Mn or Mo content, the microstructure changes from ferrite plus pearlite to ferrite plus martensite. The change in microstructure is accompanied by a suppression of the yield point elongation and a lowering of the yield strength and yield ratio.

Fig. 6 depicts the effects of cooling rate and Mn content on yield point elongation and yield ratio (a) and yield strength (b). A distinction between ferrite plus pearlite and dual phase structures is made by the yield point elongation of 1 %, and is shown as a solid line in the figure. The dual-phase structure is obtained in the right-hand side of this line. Dotted lines represent equi-yield-ratio curves (a) and equi-yield-strength curves (b). Three dashed lines (b) represent the decrease in tensile strength by 2, 5, and 10 kg/mm<sup>2</sup> due to ageing for 20 min. at 170 °C. The amount of decrease in tensile strength can be a measure of excessively dissolved carbon concentration in ferrite, which must be tempered to improve ductility. Whether or not tempering is necessary is decided here by the decrease in tensile strength by 2 kg/mm<sup>2</sup>. Accordingly dual phase steel free from tempering can be obtained in the triangular region surrounded by the solid line and the 2 kg/mm<sup>2</sup> dashed line.

As seen in Fig. 6 (b), equi-yield-strength curves are obtained in a Mn content versus cooling rate diagram. At a constant cooling rate, lower yield strength is obtained with increasing Mn content in dual phase region. For a given equi-yield-strength curve, there is an optimum cooling rate required to minimize the Mn content of the steel. On either side of the optimum cooling rate, a higher alloy content is required to keep the same yield strength. The optimum cooling rate is shifted to a higher cooling rate with decreasing Mn content. The optimum cooling rates are 70 °C/s and



Notes: A pair of digits in (a) represents yield point elongation and yield ratio, respectively. Solid line partitions dual phase (right) and ferrite-pearlite (left) regions. Broken line represents amount of decrease in tensile strength due to ageing at 170°C for 20 min. Dotted line represents equi-yield ratio or equi-yield-strength curve.

Fig. 6 Effects of Mn content and cooling rate on (a) yield point elongation and yield-to-tensile strength ratio and (b) yield strength

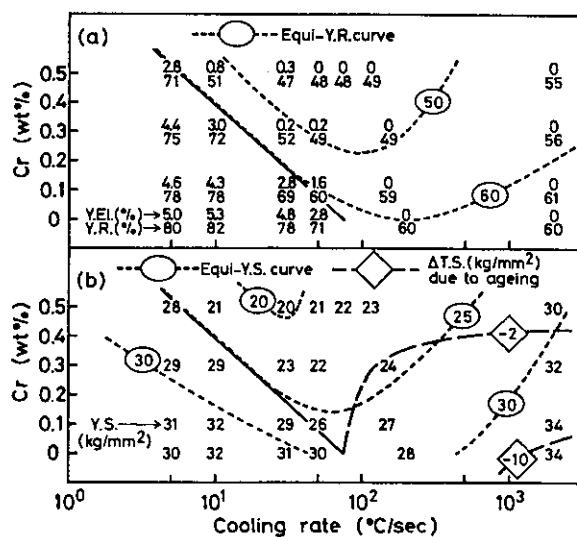


Fig. 7 Effects of Cr and cooling rate on (a) yield point elongation and yield-to-tensile strength ratio and (b) yield strength

150 °C/s for 25 kg/mm<sup>2</sup> and 30 kg/mm<sup>2</sup>, respectively.

Fig. 7 shows the effects of cooling rate and Cr content on yield point elongation and yield ratio (a), and yield strength (b) in 1.2 %Mn-Cr steels. As was the case for the Mn-added steels, the Cr content versus cooling rate diagram is divided into two regions: ferrite-pearlite and dual phase structure regions. The latter is further divided into non-tempering and tempering regions. Both equi-yield-ratio and equi-yield-strength curves are plotted. At a constant cooling rate, the yield strength and yield ratio decrease with increasing Cr content. For each contour there is an optimum cooling rate required to minimize Cr content of the steel. The minimum Cr contents are 0 %, 0.16 % and 0.5 % for the 30 kg/mm<sup>2</sup>, 25 kg/mm<sup>2</sup> and 20 kg/mm<sup>2</sup> contours, respectively. The optimum cooling rates are 150 °C/s, 40 °C/s and 25 °C/s for the 30 kg/mm<sup>2</sup>, 25 kg/mm<sup>2</sup> and 20 kg/mm<sup>2</sup> contours, respectively.

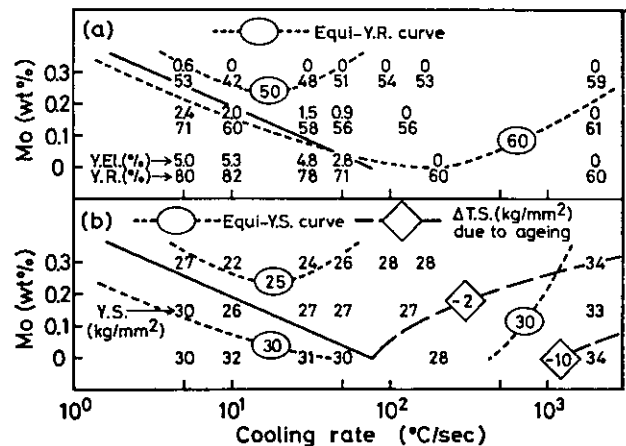


Fig. 8 Effects of Mo and cooling rate on (a) yield point elongation and yield-to-tensile strength ratio and (b) yield strength

Fig. 8 depicts the effects of cooling rate and Mo content on the yield point elongation and yield ratio (a) and the yield strength (b) in the Mo-added steels. The result obtained is almost the same as those for the Mn-added and Cr-added steels.

## 4 Discussion

### 4.1 Relation between Alloy Content and Critical Cooling Rate

As shown in Figs. 6 to 8, with the increase in cooling rate and/or alloy content, the deformation behavior changes from a sharp yield drop to continuous yielding, corresponding to a change in microstructure from the ferrite plus pearlite to the ferrite plus martensite dual phase structure. The critical cooling rate

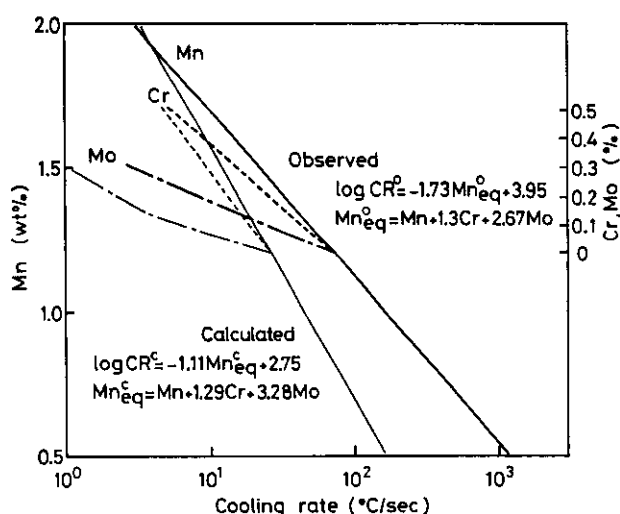


Fig. 9 Relation between alloy content and critical cooling rate required for formation of dual phase structure

required for the formation of the dual phase structure is obtained from Figs. 6 to 8, and is plotted as a function of alloy content in Fig. 9 where a comparison is made with the calculated ones. The logarithm of the critical cooling rate decreases in a linear manner with increasing Mn content. Since Mn can be substituted by Mo and/or Cr, the effect of alloying elements on the critical cooling rate,  $CR^0$  ( $^{\circ}C/s$ ), can be expressed in terms of the manganese equivalent,  $Mn_{eq}^0$  (%):

$$\log CR^0 (^{\circ}C/s) = -1.73Mn_{eq}^0(\%) + 3.95 \quad (3)$$

$$Mn_{eq}^0(\%) = Mn(\%) + 1.3Cr(\%) + 2.76Mo(\%) \quad (4)$$

The equations (1) and (2) derived from calculation and the equations (3) and (4) derived from experiment show the same tendency qualitatively as for the effect of the alloying elements on the critical cooling rate. However, the calculated critical cooling rate is smaller than the experimental values, and whereby the coefficient of  $Mn_{eq}^0$  is smaller than that of  $Mn_{eq}^0$ . Such difference can be decreased by correcting the parameters used in the calculation.

#### 4.2 Necessity of Over-ageing

As shown in Figs. 6 to 8, with the decrease in alloy contents and the increase in the cooling rate, the decrease in tensile strength  $\Delta T.S.$  due to ageing at  $170^{\circ}C$  for 20 min. becomes large. K. Nakaoka, et al.<sup>3)</sup> reported that the dual phase sheet steel manufactured by water quenching showed such decrease in tensile strength. That is, in the case of water-quenched dual phase sheet steel, the state during heating in  $\alpha$ - $\gamma$  range is frozen and oversaturated solute C

remains in  $\alpha$  phase in as-cooled condition. This oversaturated C is decreased by ageing at  $170^{\circ}C$ . Upon tempering,  $\alpha'$  as well as  $\alpha$  strengthened by the oversaturated C are softened, resulting in the decrease in tensile strength. Water quenched dual phase steel is required to be overaged to decrease the amount of the solute C<sup>3)</sup> in ferrite and to give good ductility. According to the present experiment, decrease in tensile strength due to over-ageing is observed not only in water quenched steel but also in the steel with relatively slow cooling rate, in particular, in  $\alpha + P$  steel containing low Mn content. In addition, decrease in tensile strength occurs in both  $\alpha + P$  and  $\alpha + \alpha'$  structures. It was reported that at temperatures below  $200^{\circ}C$ , the effect of the alloying element such as Mn, Cr, Mo, etc. on softening due to tempering of martensite is small<sup>9)</sup>. Taking into consideration this fact, the change in  $\Delta T.S.$  is considered to be mainly caused by the change in the amount of the solute C in  $\alpha$  phase.

The amount of the solute C in the  $\alpha$  phase of water quenched steel was measured by the internal friction method. In this measurement, after quenching in water, the specimens were kept in a freezer at  $-20^{\circ}C$  until they were measured to prevent ageing at the room temperature. Fig. 10 shows the results of the measurement.

$Q^{-1}$  decreases with the increase in alloy content. Fig. 10 also shows the calculated effects of Mn, Cr and Mo on the C content which is dissolved in  $\alpha$  phase in balance to the  $\gamma$  phase at  $770^{\circ}C$ . In this calculation, para equilibrium<sup>10)</sup> was assumed and the interaction between the alloying elements and C was ignored. With increase in Mn and Cr content, the solubility of C in  $\alpha$  phase decreases. With increase in Mo content, the solubility of C in  $\alpha$  phase increases. However, the actual solubility of C will be lower than the calculated value due to the interaction between Mo and C. It

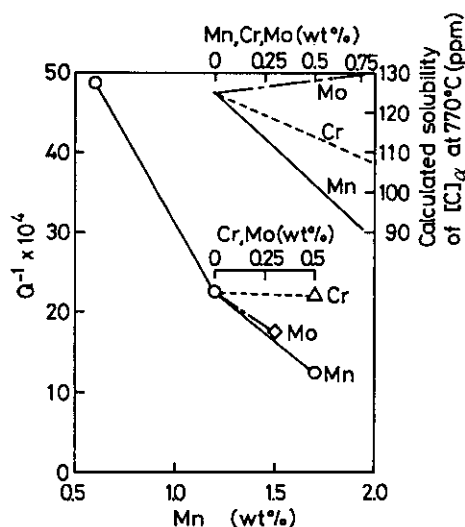


Fig. 10 Relation between alloy contents and  $Q^{-1}$

must, however, be emphasized that because of the complicated influence of alloying elements and the dual phase structure on  $Q^{-1}$ , it is difficult to correctly measure solute C content from  $Q^{-1}$ . It can be concluded from the calculation and measured  $Q^{-1}$  values that with the increase in the content of the alloying elements, the content of the solute C in  $\alpha$  phase decreases.

Summarizing the results described so far, when steel is cooled at the cooling rate greater than the value corresponding to  $\Delta T.S.$ , for example,  $-2\text{kg/mm}^2$ , shown in Figs. 6 to 8, overaging is required after the annealing process.

### 4.3 Yield Strength of Dual Phase Steel

As shown in the equations (3) and (4), the critical cooling rate required for the formation of the dual phase is not affected by replacing Mn, Cr and Mo with each other. However, the influence of alloying elements such as Mn, Cr and Mo on the tensile properties is not necessarily the same. As shown in Figs. 6 to 8, equi-Y.S. curves are different in shape among the three alloying elements: Mn-Cr steel has the shallowest curve, implying less sensitivity to variations in cooling rate and alloy content. In the case of water quenched steel, as shown in Fig. 11, the effect of the alloying elements on the yield strength is different from each other. Fig. 11 shows both yield strengths of specimens which were kept at room temperature for about 1 week after water quenching prior to tensile testing and those of specimens which were kept in a freezer at  $-20^\circ\text{C}$  to prevent aging at room temperature. In the specimens aged at the room temperatures for 1 week, yield strength decreases with the increase in alloy content, which is particularly remarkable in Cr steel. In the specimens kept at  $-20^\circ\text{C}$  yield strengths are generally low and increases with the

increase in Mn content. This fact clearly shows that aging proceeds at room temperature in specimens as-quenched. Age hardening was caused by fine carbide precipitated at the room temperature, as reported by K. Tsunoyama, et al<sup>11)</sup>. The ageing at room temperature will vary depending on the kind and amount of alloying element. With the decrease in alloy content and increase in solute C content in  $\alpha$  phase, the increase in yield strength becomes larger.

As described above, the tensile properties, especially, the yield strength are not necessarily affected in the same manner by the kind of the alloying elements and the cooling rate. It is considered that the yield strength of dual phase steel is affected by the fraction of  $\alpha'$  phase, the kind and the distribution of the second phase, grain size of ferrite, the strength of  $\alpha$  phase etc. These factors will be discussed in the following.

The authors<sup>12)</sup> studied the effect of the  $\alpha'$  fraction on the yield strength by using 0.1–0.6 % C steel, which showed that the yield strength of dual phase steel was almost constant in the range of fraction of  $\alpha'$  less than about 30 %. In this experiment, the samples containing different content of C were heated at the same temperature in the  $\alpha$ - $\gamma$  range and quenched into water. Therefore, dual phase steels with the same composition in  $\alpha$  and  $\alpha'$  phases and with wide range of  $\alpha'$  fraction were obtained. As described above, in this experiment, the heating temperature was selected at  $770^\circ\text{C}$  so that  $\gamma$  fraction became about 25 % during heating, so no sample showed  $\alpha'$  fraction higher than 30 %. Therefore the yield strength of the steels used in this experiment are hardly affected by  $\alpha'$  fraction.

The authors studied the effect of the grain size on the yielding behavior of dual phase steel and found out that  $k_y$  in the Hall-Petch relation ( $\sigma_y = \sigma_0 + k_y d^{-1/2}$ ) was very low, i.e., as low as about 1/3 of  $k_y$  in  $\alpha + \text{P}$  steel<sup>13)</sup>. Since there is little change in  $\alpha$  grain size among all the steels, it is considered that  $\alpha$  grain size has only slight influence on the yield strength, suggesting that the yield strength of dual phase steel is mainly affected by  $\sigma_0$ , the frictional stress which is required to move dislocations in ferrite matrix.

Judging from the above mentioned facts, in order to obtain low yield strength it is necessary to keep the  $\alpha$  phase as clean as possible, i.e., to decrease solute C content as low as possible. By this method, it is expected to achieve low yield strength and to improve ductility at the same time. Solute C content in the  $\alpha$  phase in cooled condition depends on solute C content in  $\alpha$  phase during heating and the subsequent cooling rate. As shown in Fig. 10, solute C content during heating varies depending on alloying element, and when steel is cooled at adequate cooling rate, C atoms migrate from  $\alpha$  phase to the coexisting  $\gamma$  phase, resulting in the stabilization of  $\gamma$  phase. As a result,

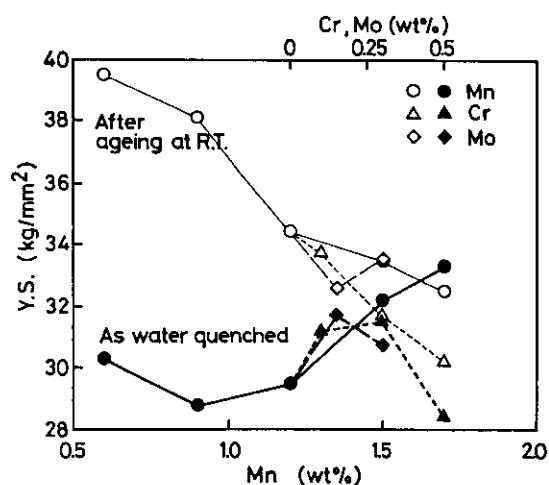


Fig. 11 Effects of alloy contents and ageing on Y.S. of water-quenched dual phase steel



the Ms temperature is lowered and the temperature range where carbon atoms can migrate from  $\alpha$  to  $\gamma$  phase becomes wider. To utilize the scavenge effect of C atom from  $\alpha$  phase as effectively as possible, it is desirable to cool steel slowly at an adequate cooling rate. In addition, to obtain dual phase structure by this slow cooling, the alloy content more than the certain level is required. When the composition of steel is kept constant, the solute C content decreases with the decrease in the cooling rate, resulting in the decrease in yield strength and  $\Delta T.S.$  as shown in Figs. 6 to 8. It is considered that the yield strength increases in the vicinity of the critical cooling rate because this region is a transition range from  $\alpha + \alpha'$  to  $\alpha + P$ , that is, microstructure in this region consists of  $\alpha$ ,  $\alpha'$  and P. At the constant cooling rate with the increase in alloy content, the yield strength and the  $\Delta T.S.$  decrease because of the decrease in solute C content in  $\alpha$  phase. As shown in Fig. 11, for example, in the case of water quenched steel, with the decrease in alloy content, solute C content increases and the yield strength increases due to ageing at room temperature. However, without the ageing effect at room temperature, the yield strength increases with the increase in the Mn content but decreases with the increase in the Cr content.

Therefore, the change in the yield strength cannot be explained only in terms of solute C content. Yield strength of ferrite changes markedly with the slight change in the carbon content. The yield strength of ferrite also changes with the change in the alloy content. It was reported that the yield strength of ferrite increase by +460, +3.2, -3.0 and +1.1 kg/mm<sup>2</sup>, respectively, with the addition of 1 % of C, Mn, Cr and Mo<sup>14</sup>. Mn and Mo increase the yield strength by solid solution hardening. However, Cr has no solid solution hardening effect. Using these value and solute C content derived from  $Q^{-1}$  shown in Fig. 10, the effects of alloy content and solute C content on yield strength are roughly calculated. It is found out that the changes in yield strength in 0.6 % Mn steel, 1.7 % Mn steel, 1.2 % Mn-0.5 % Cr and 1.2 % Mn-0.3 % Mo steel are -0.3, +1.0, -1.6 and 0 kg/mm<sup>2</sup>, respectively, by using the yield strength of 1.2 % Mn steel as the reference value. The results of this approximate calculation agree well qualitatively with the change in yield strength of the samples in quenched condition, shown in Fig. 11. In other words, the change in yield strength in steel containing Mn or Mo is the additive effect of the decrease in the yield strength due to the decrease in solute C content and the increase in the yield strength due to the solid solution hardening by Mn or Mo. In the case of steel containing Cr, yield strength decreases due to the decrease in the solute C content, while causing no solid solution hardening.

As described above, the yield strength of dual phase sheet steels mainly depends on the strength of  $\alpha$  phase. However, it is also affected by the kind and the distribution of the second phase. Actually, in the case of steel containing Mn and Mo shown in Figs. 6 and 8, the yield strength increases with the coexistence of pearlite at the transition region. The effects of the kind and the distribution of second phase must be further studied in the future.

#### 4.4 Optimal Manufacturing Conditions of Dual Phase Sheet Steels

The relation between cooling rate, alloy content and physical properties is schematically shown in Fig. 12. The diagram can be divided into three regions: the ferrite-pearlite region, the non-tempering dual phase region and the tempering dual phase region. The boundary line between the ferrite-pearlite and the dual phase regions is decided by the critical cooling rate required to accomplish the martensite transformation. Tempering is required to decrease excessively dissolved C, and thereby to improve ductility and the strength-elongation relationship. In the tempered condition, fine cementite particles are dispersed in the ferrite matrix<sup>31</sup>. In the non-tempering region, the ferrite matrix is almost free from solute C and precipitates since C atoms are absorbed by the austenite during cooling. In the non-tempering region, equi-yield-strength curves are drawn, which are dependent on alloy content. With an increase in alloy content, the yield strength decreases. The difference in yield strength between the two equi-yield-strength curves is determined by the decrease in yield strength due to the decrease in dissolved C and the increase in yield strength due to solid solution hardening.

Dual phase steel can be produced by a wide variety of chemical compositions from low C to relatively

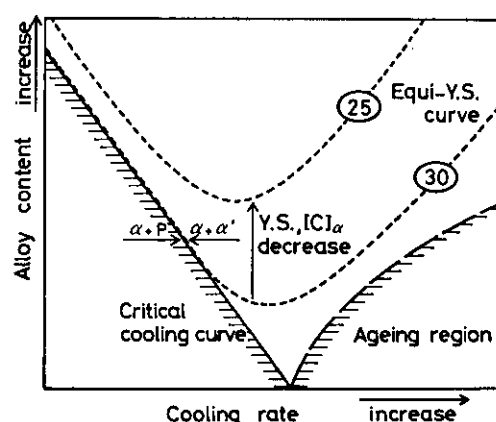


Fig. 12 Schematic illustration of phase regions in cooling rate—alloy content diagram: Diagram is divided into ferrite-pearlite, dual phase and tempered (overaged) dual phase regions

high alloy steels associated with adequate cooling rate. As shown in Figs. 6 to 8, however, there is an optimum combination of chemical composition and cooling rate and better tensile properties are obtained only when a higher alloy steel is cooled neither too slowly nor too rapidly. High alloy steels are also less sensitive to the variation in chemical composition and cooling rate. When the 0.05 %C–1.2 %Mn–0.5 %Cr steel is cooled at the rate of 30 °C/s, a low yield strength of 20 kg/mm<sup>2</sup>, a yield ratio as low as 0.4 and a total elongation of more than 40 % are obtained (see Fig. 1).

## 5 Conclusions

For the purpose of producing dual phase steel with superior formability, the effects of alloying element and cooling rate on the formation and properties of dual phase steel were studied in detail. The results obtained are summarized in the following.

- (1) The diagram of alloy content-cooling rate-physical properties is divided into three regions: ferrite-pearlite regions, a non-tempering dual phase region and a tempering dual phase region.
- (2) The logarithm of the critical cooling rate required for the formation of the dual phase structure, decreases in a linear manner with increasing manganese equivalent,  $Mn_{eq}$ , as expressed by  $\log CR(^{\circ}C/s) = -1.73Mn_{eq}(\%) + 3.95$ , where  $Mn_{eq}(\%) = Mn(\%) + 1.3Cr(\%) + 2.67Mo(\%)$ .
- (3) A 0.05 %C–1.2 %Mn–0.5 %Cr dual phase steel shows the most favorable deformation behavior:

a low yield strength of 20 kg/mm<sup>2</sup> and a yield-to-tensile strength ratio as low as 0.4.

- (4) The addition of Cr is favorable since it decreases the dissolved C content by promoting the partition of C between austenite and ferrite, while it does not cause solid solution hardening in ferrite.

## References

- 1) N. Ohashi, I. Takahashi and K. Hashiguchi: Trans. ISIJ, **18** (1968), p. 321
- 2) S. Hayami, T. Furukawa and Y. Takeoka: Tetsu-to-Hagané, **61** (1975) 4, p. 148
- 3) K. Nakaoka, K. Araki and S. Kinbara: J. Japan Soc. for Technology of Plasticity, **17** (1976) 190, p. 875
- 4) K. Hashiguchi, M. Nishida, T. Kato and T. Tanaka: Tetsu-to-Hagané, **64** (1978) 4, p. 257
- 5) M. Takahashi, K. Kunishige, J. Murayama and T. Masui: Tetsu-to-Hagané, **64** (1978) 11, p. 803
- 6) M.S. Rashid: SAE Report, (1976), 760206
- 7) J.H. Bucher and E.G. Hamburg: SAE Report, (1977), 7700164
- 8) Y. Ito, Y. Sakamoto, M. Saeki, Y. Saito, S. Takizawa and T. Higashino: Tetsu-to-Hagané, **64** (1978) 11, p. 806
- 9) R.A. Grange, C.R. Hribal and L.F. Porter: Met. Trans. **8A**, (1977), p. 1775
- 10) F. Togashi and T. Nishizawa: Journal of the Japan Institute of Metals, **40** (1976) 1, p. 12
- 11) K. Tsunoyama, K. Matsumura and K. Tsuruoka: Preprint of Journal of the Japan Institute of Metals, (1972), p. 35
- 12) T. Kato, M. Nishida, K. Hashiguchi and T. Tanaka: Unpublished work
- 13) T. Tanaka, M. Nishida, K. Hashiguchi and T. Kato: "Symposium on Structure and Properties of Highly Formable Dual-Phase HSLA Steels-I", 108th AIME Annual Meeting, (1979)
- 14) F.B. Pickering: Physical Metallurgy and the Design of Steels, (1978), p. 70 [Applied Science Publishers Ltd.]