The Effects of Metallurgical Factors on Fatigue Strengths

(Part 3, The Effects of C, Si, Mn, P and Cu (2))*

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The effects of C, Si, Mn, P and Cu in quenched and tempered low carbon steels on fatigue strength were investigated, and the results were extended to higher carbon steels.

Sixteen kinds of steels containing above alloying elements were prepared according to a statistical design. The results of tensile and fatigue tests were processed by variance analysis and multiple regression analysis methods.

The conclusions are as follows.

(1) The relation between fatigue limit and alloying elements can be formulated by multiple regression analysis method.

(2) The relation between fatigue limit $\bar{\sigma}_w$ and yield strength $\bar{\sigma}_s$ can be formulated as follows.

$$\bar{\sigma}_w = 0.426 \bar{\sigma}_s + \{29(P-0.066) + 5.0(Cu-0.71) + 16.7\}$$

(3) In the case of normalizing, the effects of C, Si, Mn, P and Cu on yield strength are more closely related to fatigue strength than to tensile strength. In the case of quenching and 650°C tempering, however, the effects of C and Mn are more closely related to tensile strength, and those of P and Cu are to fatigue strength.

1. Introduction

This report describes the effects of the most fundamental alloying elements, C, Si, Mn, P and Cu, on fatigue strengths of steels, that is a part of the studies on the effects of metallurgical factors on them. It is shown in Part 1 that fatigue limit $\bar{\sigma}_w$, fatigue notch factor β and fatigue ratio FR can be shown as functions of yield strength $\bar{\sigma}_s$ or tensile strength $\bar{\sigma}_B$ and the alloying elements, when $\bar{\sigma}_s$, $\bar{\sigma}_B$ and $\bar{\sigma}_w$ are expressed as functions of alloying elements with a parameter of heat treatment condition. Especially, it was shown that $\bar{\sigma}_w$ was more closely related to $\bar{\sigma}_s$ than to $\bar{\sigma}_B$.

In Part 2⁽²⁾, fatigue limit of plain specimen $\bar{\sigma}_w$ was shown to be expressed also as a function of quantities of alloying elements with high contribution in the same way as $\bar{\sigma}_s$ and $\bar{\sigma}_B$ in normalized carbon steels, as suggested in Part 1. The dependence of $\bar{\sigma}_w$ on alloying elements was shown to have a similarity to that of $\bar{\sigma}_s$, and it was suggested that the relation between $\bar{\sigma}_w$ and $\bar{\sigma}_s$ shown in Part 1 was not only phenomenologically general but also substantial.

In this experiment, the same kind of analysis on the same materials as in Part 2 was performed in the case

of quenching and 650°C tempering. Namely, $\bar{\sigma}_s$, $\bar{\sigma}_B$, $\bar{\sigma}_w$ were obtained as functions of quantities of alloying elements. These relations seem to be very important for the selection of structural materials for fatigue design and their heat treatment condition and for the development of new steels.

2. Method of analysis

As yield strength $\bar{\sigma}_s$ can be expressed as Eq. (1) with high contribution, same kind of Equation (2) is assumed to hold, as suggested in Part 1 and confirmed in Part 2.

$$\bar{\sigma}_s(T) = \sum_{i=1}^n b_i(T)(e_i - \bar{e}_i) + \sum_{i,j=1}^n b_{ij}(T) \cdot (e_i - \bar{e}_i)(e_j - \bar{e}_j) + \bar{\sigma}_{s0}(T) \dots \dots \dots (1)$$

$$\bar{\sigma}_w(\alpha, T) = \sum_{i=1}^n c_i(\alpha, T)(e_i - \bar{e}_i) + \sum_{i,j=1}^n c_{ij}(\alpha, T)(e_i - \bar{e}_i)(e_j - \bar{e}_j) + \bar{\sigma}_{w0}(\alpha, T) \quad (2)$$

T : heat treatment condition

e_i : kind and quantity of alloying element

$\bar{e}_i$: mean quantity of element

$b_i(T)$, $c_i(\alpha, T)$: regression coefficients showing main effects of e_i on $\bar{\sigma}_s$ and $\bar{\sigma}_w$, respectively

$b_{ij}(T)$, $c_{ij}(\alpha, T)$: regression coefficients showing interaction effects between e_i and e_j on $\bar{\sigma}_s$ and $\bar{\sigma}_w$, respectively

α : stress concentration factor

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When e_i is eliminated from Eqs. (1) and (2), Equation (3) is derived.

$$\begin{aligned}\sigma_w(\alpha, T) &= K(e_1, \alpha, T) \sigma_s(T) + H(e, \alpha, T) \\ K(e_1, \alpha, T) &= c_1(\alpha, T) / b_1(T) \\ H(e, \alpha, T) &= \left\{ \sum_{i,j=1}^n c_{ij}(\alpha, T) (e_i - \bar{e}_i) + \sum_{i,j=1}^n \sum_{k,l=1}^n c_{ijkl}(\alpha, T) (e_i - \bar{e}_i) (e_j - \bar{e}_j) + \sigma_{wo}(\alpha, T) \right\} \\ &\quad - K(e_1, \alpha, T) \left\{ \sum_{i=1}^n b_i(T) (e_i - \bar{e}_i) + \sum_{i,j=1}^n b_{ij}(T) (e_i - \bar{e}_i) (e_j - \bar{e}_j) + \sigma_{so}(T) \right\} \dots (3)\end{aligned}$$

It is shown above that σ_w can be expressed by linear equation of σ_s , and the section and the gradient are functions of alloying elements. Especially, the section has the form of subtraction, so that the value is not sensitively affected by elements. As it has significant effect on strength at a little quantity, carbon is suitable as the element to be eliminated.

In general, even if there are differences between the estimated values of σ_w and σ_s , and the measured values of them, the deviation has same direction. When the measured value of σ_w , for instance, is larger than the estimated value, the measured value of σ_s is larger than the estimated value, too. Therefore it is more favorable that the estimating equation is composed of "strength term" as shown in Eq.(3) than it is composed of only "composition terms" as shown in Eq.(2).

Then Equation (4) is defined as a fundamental equation.

$$\sigma_w(\alpha, T) = K(e_1, \alpha, T) \sigma_s(T) + H(e, \alpha, T) \dots (4)$$

when $e_1 = C$ (carbon)

$$K(C, 1, T) = 0.426$$

for T=normalizing, quenching and 450~650°C tempering.

$$K(C, 3, T) = 0.116$$

for T=normalizing, quenching and 650°C tempering.

H : function of alloying element without main effect of carbon
Equation (4) is the estimating equation of σ_w by σ_s with correction term of alloying elements. The principal factors effecting the correction term can be derived by conducting variance analysis on H values which are obtained from equation, $H = \sigma_w - K\sigma_s$, after σ_w and σ_s are measured. Then, H term can be determined quantitatively by multiple regression analysis on H values.

Though the relation between σ_w and σ_s can be obtained in such a form as Eq.(3), it is shown that K values will change depending on heat treatment condition⁽¹⁾. On the other hand, it is shown that the relation between σ_w and σ_s is more general⁽²⁾ and more reasonable substantially.⁽²⁾

In this report are shown in the form of Eqs.(1), (2) and (4) the effects of C, Si, Mn, P and Cu on fatigue strength of quenched and 650°C tempered low carbon steels.

3. Experimental method

3.1 Materials

The arrangement of chemical com-

Table 1. Levels of compositions, %
Numbers in parentheses show mean values after analysis

Level	C	Si	Mn	P	Cu
1	0.11 (0.12)	0.25 (0.27)	0.50 (0.55)	0.04 (0.038)	0.50 (0.45)
2	0.16 (0.17)	0.50 (0.50)	1.00 (0.95)	0.09 (0.094)	1.00 (0.98)

Table 2. Orthogonal array table of factors and their levels

Steel	Factor	C	Si	Mn	P	Cu
A 1	1	1	1	1	1	1
A 2	1	1	1	2	2	2
A 3	1	1	2	1	2	2
A 4	1	1	2	2	1	2
A 5	1	2	1	1	2	2
A 6	1	2	1	2	1	1
A 7	1	2	2	1	2	1
A 8	1	2	2	2	2	2
A 9	2	1	1	1	1	2
A 10	2	1	1	2	2	1
A 11	2	1	2	1	1	1
A 12	2	1	2	2	2	2
A 13	2	2	1	1	1	1
A 14	2	2	1	2	2	2
A 15	2	2	2	1	1	2
A 16	2	2	2	2	2	1

Table 3. Chemical compositions, %

Steel	C	Si	Mn	P	S	Cu
A 1	0.12	0.25	0.54	0.039	0.016	0.43
A 2	0.12	0.27	0.53	0.088	0.014	0.98
A 3	0.12	0.26	0.96	0.036	0.015	1.00
A 4	0.12	0.26	0.98	0.092	0.015	0.52
A 5	0.14	0.51	0.55	0.037	0.014	0.95
A 6	0.12	0.49	0.53	0.092	0.015	0.45
A 7	0.13	0.54	1.02	0.034	0.017	0.44
A 8	0.10	0.48	0.97	0.093	0.016	0.98
A 9	0.18	0.28	0.57	0.040	0.015	0.98
A 10	0.17	0.28	0.56	0.099	0.017	0.44
A 11	0.19	0.27	0.86	0.043	0.014	0.43
A 12	0.18	0.29	1.02	0.096	0.017	0.97
A 13	0.14	0.47	0.54	0.039	0.015	0.44
A 14	0.19	0.54	0.57	0.094	0.017	0.98
A 15	0.17	0.51	0.97	0.039	0.017	0.99
A 16	0.15	0.49	0.85	0.097	0.016	0.44

Table 4. Results of tensile test and fatigue test

Steel	σ_s kg/mm ²	σ_B kg/mm ²	φ %	ψ %	σ_{wo} kg/mm ²	H kg/mm ²
A 1	39.9	54.9	29.0	73.9	31.0	14.0
A 2	52.9	65.0	29.0	72.1	42.4	19.9
A 3	56.6	67.5	26.0	72.2	42.0	17.9
A 4	55.4	67.5	28.5	71.7	40.2	16.6
A 5	50.5	63.1	30.5	70.9	41.0	19.5
A 6	46.9	62.4	32.0	69.8	37.0	17.0
A 7	52.1	62.4	27.0	67.7	37.2	15.0
A 8	58.7	69.8	27.5	68.2	44.0	19.0
A 9	54.4	67.1	26.0	67.4	40.5	17.3
A 10	50.0	66.6	28.5	67.4	37.2	15.9
A 11	57.3	70.6	21.0	67.4	38.0	13.6
A 12	67.3	77.9	26.0	65.3	45.8	17.1
A 13	47.6	63.5	29.5	68.2	35.5	15.2
A 14	58.2	72.0	27.5	66.2	44.3	19.5
A 15	67.3	75.6	26.5	67.4	43.2	14.5
A 16	58.2	72.2	27.5	67.4	41.0	16.2

positions, C, Si, Mn, P and Cu, of test materials were designed with type $L_{16}(2^5)$ orthogonal array in experimental planning method to obtain the main effects and the interaction effects between two kinds of factors, that is,

compositions. The levels of factors are shown in Table 1. The sixteen kinds of 50 kg steels were melted according to the array shown in Table 2. The chemical compositions analyzed are shown in Table 3. The ingots were forged to 20 mm diameter rods, and were heat treated under the conditions of 940°C, 1h, WQ-650°C, 1h, AC. Some typical microstructures are shown in Fig.1.

3.2 Method of tests.

Static strengths were obtained with JIS.No.4 type specimen (14 mm dia., 50 mm gage length), and 0.2% proof stress was adopted for σ_s .

One type rotating bending fatigue testing machines were used for the tests. The specimens were longitudinally polished with No.03 emery paper in final state. The shape of specimen is shown in Fig.2. S/N curves were drawn through the midst of about 10 test points, and fatigue limits were obtained by extrapolating the curves to 10^7 cycles.

4. Analysis of results

The results of tensile and fatigue tests are shown in Table 4. The values, $H = \sigma_{wo} - 0.426 \cdot \sigma_s$, are shown together in the table. The results of variance analysis on the characteristic values, σ_s , σ_B , σ_{wo} and H , are shown in Tables 5~8. Though all the main and interaction effects of the five kinds of elements were calculated, factors with little effects were pooled in error term. Then multiple regression analysis was made on the relation between characteristic values and factors that were verified to be significant, and the regression equations obtained are given as Eqs.(5)~(8). The quantities of elements and stress have units of % and kg/mm², respectively. Equations (5) and (7) correspond to Eqs.(1) and (2), respectively. Equation (8) corresponds to H term in Eq.(4), and therefore equation corresponding to Eq.(4) results in Eq.(9).

$$\sigma_s = 103(C-0.15) + 22(Mn-0.75) + 56(P-0.066) + 11(Cu-0.71) + 54.3 \quad \dots (5)$$

$$\sigma_B = 108(C-0.15) + 14(Mn-0.75) + 74(P-0.066) + 6.7(Cu-0.71) + 40.0 \quad \dots (6)$$

$$\sigma_{wo} = 24(C-0.15) + 6.3(Mn-0.75) + 52(P-0.066) + 10(Cu-0.71) + 40.0 \quad \dots (7)$$

$$H = 29(P-0.066) + 5.0(Cu-0.71) + 16.7 \quad \dots (8)$$

$$\sigma_{wo} = 0.426\sigma_s + \{29(P-0.066) + 5.0(Cu-0.71) + 16.7\} \quad \dots (9)$$

5. Discussion

5.1 Extension of application regions of multiple regression equations. The applied regions of Eqs.(5)~(7) and (9) are about the same as the intervals of the levels shown in Table 1. Here it is tried to extend the regions to the results on carbon steels.

(a) Steel A 8 (b) Steel A16
Fig.1 Examples of microstructure

Fig.2 Shape of fatigue test specimen

The estimating equations of σ_s , σ_B and σ_{wo} as functions of quantity of C on quenched and 650°C tempered standard carbon steels are shown as Eqs.(10)~(12) which were obtained in previous experiments the results of which are shown in Table 9.⁽⁶⁾

$$\sigma_s = 66C + 31.2 \quad \dots (10)$$

$$\sigma_B = 63C + 47.1 \quad \dots (11)$$

$$\sigma_{wo} = 30C + 25.5 \quad \dots (12)$$

As Mn contents of these materials were almost the same as those in this investigation though there exists interaction between Mn and C, the regression coefficients of C in Eqs.(10)~(12) correspond to those in equations when applied regions are extended to C. Then the equations, when applied regions of C are extended to 0.09~0.64%, can be expressed as Eqs.(13)~(15).

$$\sigma_s = 66(C-0.15) + 22(Mn-0.75) + 56(P-0.066) + 11(Cu-0.71) + 54.8 \quad \dots (13)$$

$$\sigma_B = 63(C-0.15) + 14(Mn-0.75) + 74(P-0.066) + 6.7(Cu-0.71) + 67.7 \quad \dots (14)$$

$$\sigma_{wo} = 30(C-0.15) + 6.3(Mn-0.75) + 52(P-0.066) + 10(Cu-0.71) + 40.0 \quad \dots (15)$$

As the contents of P and Cu of the steels shown in Table 9 are beyond the applied regions of Eqs. (5)~(7), the equations with the regression coefficient of C changed do not necessarily include the steels shown in Table 9. If the differences between the estimated values and the measured values, however, are small, these steels can be considered to be included. If Equation (9) describes well the results shown in Table 9, the applied region of the equation could be considered to be extended, too.

Then in Figs. 3~6 are shown the comparisons of the measured values and the estimated values obtained by sub-

Table 5. Variance analysis table on yield strength

Factor	Sum of squares	Degree of freedom	Mean square	F-ratio	$F_{10}^1(0.05)$	$F_{10}^1(0.01)$
C	139.8	1	139.8	53.6**	4.96	10.0
Mn	328.5	1	328.5	126**		
P	30.0	1	30.0	11.5**		
Cu	213.8	1	213.8	81.9**		
SixP	10.4	1	10.4	3.98		
Error	26.1	10	2.61			
Total	748.6	15				

* 5% significant ** 1% significant

Table 6. Variance analysis table on tensile strength

Factor	Sum of squares	Degree of freedom	Mean square	F-ratio	$F_{10}^1(0.05)$	$F_{10}^1(0.01)$
C	174.9	1	174.9	157.6**	4.96	10.0
Mn	149.4	1	149.4	134.6**		
P	51.5	1	51.5	46.4**		
Cu	89.8	1	89.8	80.9**		
SixMn	7.4	1	7.4	6.7*		
Error	11.1	10	1.11			
Total	484.1	15				

* 5% significant ** 1% significant

Table 7. Variance analysis table on fatigue limit

Factor	Sum of squares	Degree of freedom	Mean square	F-ratio	$F_{11}^1(0.05)$	$F_{11}^1(0.01)$
C	7.1	1	7.1	5.5*	4.84	9.65
Mn	31.6	1	31.6	24.5**		
P	34.5	1	34.5	26.7**		
Cu	132.8	1	132.8	102.9**		
Error	14.2	11	1.29			
Total	220.2	15				

* 5% significant ** 1% significant

Table 8. Variance analysis table on H value

Factor	Sum of squares	Degree of freedom	Mean square	F-ratio	$F_{11}^1(0.05)$	$F_{11}^1(0.01)$
Mn	4.389	1	4.389	3.845	4.84	9.65
P	12.53	1	12.53	10.98**		
Cu	28.03	1	28.03	24.56**		
MnxCu	2.958	1	2.958	2.592		
Error	12.55	11	1.141			
Total	60.46	15				

** 1% significant

stituting the data in Tables 3 and 4 into Eqs.(13)~(15) and (9). In the same manner, Figs. 7~10 show the comparison obtained from Table 9. The side lines of "measured value=estimated value" show the range of ± 2 kg/mm². These figures show that the estimated values agree well with the experimental results, and show that the applied regions are as follows, C $\leq$ 0.64%, Si=0.27/0.50%, Mn=0.55/1.0%, P $\leq$ 0.1%, Cu $\leq$ 1.0%.

5.2 Effects of elements on fatigue strength.

The orders of the magnitude of regression coefficients of main effect of each alloying element in Eqs.(13)~(15) are as follows,

σ_B : P(74)>C(63)>Mn(14)>Cu(6.7)

σ_s : C(66)>P(56)>Mn(22)>Cu(11) }....(16)

σ_{wo} : P(52)>C(30)>Cu(10)>Mn(6.3)

The coefficients shown in parentheses mean the increase of strength per 1% of alloying element. The orders of coefficients on σ_s and σ_{wo} in normalized steels coincided well, but they were different from that on σ_B .⁽²⁾ These facts suggest that the strengthen-

Table 9. Mechanical properties of 0.09~0.64% carbon steels (quenched and 650°C tempered)

C	Si	Mn	P	Cu	σ_s kg/mm	σ_B kg/mm	σ_{wo} kg/mm
0.090	0.310	0.650	0.130	0.06	38.4	51.4	27.5
0.200	0.310	0.610	0.140	0.06	42.1	57.7	31.0
0.300	0.300	0.620	0.130	0.06	48.9	66.7	34.5
0.410	0.290	0.610	0.160	0.05	57.1	74.3	38.5
0.500	0.310	0.630	0.150	0.04	74.5	84.9	43.0
0.640	0.260	0.530	0.120	0.05	68.6	82.0	42.5

ing mechanisms of σ_s and σ_{wo} have a similarity. However there is no clear similarity recognized between the orders in Eq.(16). If we must choose, the orders on σ_s and σ_{wo} may be closely related to that on σ_B .

In the case of normalizing, the strengthening mechanisms of σ_B , σ_s and σ_{wo} were assumed to be independent. Then it was suggested that there exists substantial relation between the mechanisms of σ_s and σ_{wo} from the similarity of order of strengthening effects of elements in addition to the similarities of their grain size and temperature dependence.⁽³⁾

Now we put in a concrete form the

Fig.3 Comparison of estimated value with measured value on yield strength

Fig.6 Comparison of estimated value with measured value on fatigue strength

Fig.4 Comparison of estimated value with measured value on tensile strength

Fig.7 Comparison of estimated value with measured value on yield strength of 0.09~0.64% carbon steels

Fig.5 Comparison of estimated value with measured value on fatigue strength

Fig.8 Comparison of estimated value with measured value on tensile strength of 0.09~0.64% carbon steels

assumption that strengthening mechanisms are mutually independent. We recognize the general facts that the orders of strengths are as follows, $\sigma_B \geq \sigma_s \geq \sigma_{wo}$, and we assume phenomenologically the mechanisms change gradually in above order, though there exists a substantial difference in mechanisms between static and fatigue strengths. Here we examine which relation is closer, between yield

strength and tensile strength or between yield strength and fatigue strength.

The mean, maximum and minimum values of σ_{wo} and σ_B are shown as ratios in Fig.11. The data in the case of normalizing come from the

Fig.9 Comparison of estimated value with measured value on fatigue limit of 0.09-0.64% carbon steels

Fig.10 Comparison of estimated value with measured value on fatigue limit of 0.09-0.64% carbon steels

results in Part 2. As shown in Fig. 11, σ_s is nearer to σ_{wo} than to σ_B in the case of normalizing, Nor, and σ_s comes between σ_{wo} and σ_B in the case of quenching and 650°C tempering, Q&650°C-T. From above results, it follows that in the case of normalizing the mechanism of yield strength has similarity to that of fatigue strength, and in the case of quenching and 650°C tempering the mechanism of yield strength has no partial similarities to those of fatigue and tensile strengths.

Tables 10 and 11 show the results of comparison of regression coefficients of main effects. It is seen from Table 10 that the effects of elements on σ_s are more closely related to σ_{wo} than to σ_B in the case of normalizing. On the other hand, in the case of quenching and 650°C tempering the effects of C and Mn on σ_s are more closely related to those on σ_B than to those on σ_{wo} , and the effects of P and Cu on σ_s are more closely related to those on σ_{wo} than to those on σ_B as shown in Table 11. These results mean that no partial similarity mentioned above comes from the setoff of effects of elements.

Fig.11 Changes of differences between yield strength and tensile strength, and between yield strength and fatigue limit

Table 10. Comparison of regression coefficient (normalized)

	C	P	Mn	Cu	Si
σ_B/σ_s	2.55	1.77	3.28	0.54	1.98
σ_s/σ_s	1.00	1.00	1.00	1.00	1.00
σ_{wo}/σ_s	0.36	0.93	1.00	0.77	1.27

Table 11. Comparison of regression coefficient (quenched and 650°C tempered)

	C	P	Mn	Cu
σ_B/σ_s	0.95	1.32	0.64	0.61
σ_s/σ_s	1.00	1.00	1.00	1.00
σ_{wo}/σ_s	0.45	0.93	0.29	0.91

Conclusively speaking, the effect of each element differs depending on heat treatment.

5.3 Relation between fatigue strength and yield strength.

The relation between fatigue strength and yield strength can be expressed in Eq.(9) with correction terms of quantities of P and Cu. In the test materials of C, Si, Mn, P, Cu system, four informations, that is, quantities of C, Mn, P and Cu, are necessary for estimating σ_{wo} . However, it can be estimated with three informations, that is, σ_s , quantities of P and Cu, when equation (9) is used, and the accuracies of estimation by both methods are nearly equal as shown in Figs.5 and 6. Especially, H term is only a correction term, and the greater part of σ_{wo} is estimated by σ_s .

It becomes often a problem how much σ_w will change when steel is alloyed with some elements. This question has two meanings: how much the absolute value of σ_w changes and how much the ratio of σ_w to σ_s or σ_w to σ_B changes. It comes from the motives to estimate the absolute value of σ_w from static strength. Equation(9), or generally, Eq.(4), is convenient for the motive and question.

When σ_s is known, σ_{wo} of standard carbon steels for machine structure can be estimated from Eq.(17).

$$\sigma_{wo} = 0.426 \sigma_s + 13.2 \quad \dots\dots\dots (17)$$

When it is necessary to know whether or not a certain steel, σ_s and σ_{wo} of which are known, is superior to standard carbon steel, it is possible to compare the known σ_{wo} with σ_{wo} estimated from Eq.(17). If the known σ_{wo} is larger than the estimated σ_{wo} , this steel can be judged superior.

When σ_s and chemical compositions are known, it is possible to compare σ_{wo} estimated from Eq.(9) with that from Eq.(17).

As mentioned above, Equation(9) seems to be important because it can make it easy to compare between steels and give estimated value of σ_{wo} . Furthermore it is important for selection and development of steels because it shows the tendency of effects of elements by regression coefficients.

6. Conclusions

The effects of C, Si, Mn, P and Cu in quenched and 650°C tempered low carbon steels on static and fatigue strengths were statistically investigated. The results in this investigation and those in Part 1 and 2 were examined together. The conclusions are as follows.

(1) σ_{wo} can be formulated as the following multiple regression equation of alloying elements in the same way as σ_B and σ_s .

$$\sigma_s = 66(C-0.15) + 22(Mn-0.75) + 56(P-0.066) + 11(Cu-0.71) + 54.8$$

$$\sigma_B = 63(C-0.15) + 14(Mn-0.75) + 74(P-0.066) + 6.7(Cu-0.71) + 67.7$$

$$\sigma_{wo} = 30(C-0.15) + 6.3(Mn-0.75) + 52(P-0.066) + 10(Cu-0.71) + 40.0$$

where, C $\leq$ 0.65%, Si=0.27/0.50%, Mn=0.55/1.0%, P $\leq$ 0.1%, Cu $\leq$ 1.0%.

(2) The relation between σ_{wo} and σ_s can be formulated as the following equation with correction terms of alloying elements.

$$\sigma_{wo} = 0.426\sigma_s + \{29(P-0.066) + 5.0(Cu-0.71) + 16.7\}$$

(3) If it is assumed phenomenologically that the strengthening mechanisms of tensile strength, yield strength and fatigue strength change gradually in this order, the mechanism of yield strength in the case of quenching and 650°C tempering is intermediate between those of tensile and fatigue strength.

(4) From the point of view of alloying elements, the effects of C, Si, Mn, P and Cu on yield strength are more closely related to those on fatigue strength than to those on tensile strength in the case of normalizing.

The effects of C and Mn on yield strength are closely related to those on tensile strength, and the effects of P and Cu to those on fatigue strength in the case of quenching and 650°C tempering.

(5) The following equation showing the relation between fatigue strength and yield strength with correction term of alloying elements is convenient for selection and development of steels.

$$\sigma_w(\alpha, T) = K(C, \alpha, T)\sigma_s(T) + H(e, \alpha, T)$$

7. References

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