Combined Effect of Nb and Mo on the Mechanical Properties of Nb-Mo Heat-Treated High Strength Steel with 80 kg/mm² Strength Level*

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The heat treated Nb-Mo steel with 80 kg/mm² strength level, reported here, is a new type of steel which has been developed to replace the conventional T-1 type steel. The important feature of this steel is that its alloying elements are considerably reduced in number and amount. By such a reduction, the carbon equivalent (Ceq) in welding is considerably reduced and the improvement of weldability is achieved. It is rather surprising that this steel has a sufficiently high strength and toughness as 80 kg/mm² level high strength steel due to the coexistence of proper amounts of Nb & Mo, in spite of the reduction of alloying elements. In this paper, the effect of Nb and Mo upon the mechanical properties and hardenability of the new steel is investigated.

Tensile tests, Charpy tests and the Jominy tests have been carried out on the base steel, Nb treated steel, Mo steel and Nb-Mo steel. The results are compared with the values calculated according to the known formula with regard to strength and hardenability.

It has been found that the increase in strength by the duplex addition of Nb and Mo is far greater than sum total of strength obtained by the single addition of Nb and Mo, and also that the hardenability of this new steel increases by a combined effect of Nb-Mo-B tripple addition.

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I. Introduction

High strength steels with 80 kg/mm² tensile strength level have recently been a subject of active study in Japan with their increasing use as plates for pressure vessels or for penstock, and thus steels of the T-1 type of the U.S. Steel specification have been in industrial application.

The Nb-Mo Heat-treated steel with 80 kg/mm² strength level is a new type of steel developed with the specific aim of replacing the conventional T-1 type high strength steel. As shown in Table 1, the prominent feature is that its alloying elements are considerably reduced both in number and in quantity as compared with steels of the T-1 type. This enables the reduction in carbon equivalent (Ceq) in welding, thereby ensuring the improvement of weldability. It is noteworthy that this new type of steel possesses a sufficient strength and toughness as a high

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Table 1 Comparison of chemical composition.

	C	Si	Mn	Cu	Ni	Cr	Mo	V	B	Nb	Ceq
Nb-Mo HT80	0.12	0.32	1.40	—	—	—	0.56	—	0.003	0.03	0.51
T-1 HT80	0.15	0.25	0.90	0.32	0.76	0.52	0.48	0.060	0.004	—	0.56
Another HT80	0.15	0.22	0.90	0.31	—	1.01	0.47	—	0.001	—	0.64

$$Ceq = C + 1/6 Mn + 1/24 Si + 1/40 Ni + 1/5 Cr + 1/4 Mo + 1/14 V$$

Table 2 Chemical composition of steel.

Steel		C	Si	Mn	Mo	Nb	B	Al sol
Base	A	0.14	0.35	1.41	<0.03	<0.002	0.003	0.022
0.04% Nb	B	0.14	0.32	1.43	<0.03	0.040	0.005	0.024
0.6% Mo	C	0.12	0.21	1.31	0.54	<0.002	0.003	0.020
0.6% Mo	D-1	0.13	0.29	1.42	0.56	0.029	0.004	0.031
0.03-0.10% Nb	D-2	0.13	0.27	1.32	0.60	0.069	0.002	0.022
	D-3	0.14	0.27	1.43	0.59	0.100	0.004	0.021
0.3% Mo	E-1	0.14	0.28	1.42	0.29	0.035	0.003	0.021
0.03-0.10% Nb	E-2	0.13	0.24	1.41	0.31	0.061	0.002	0.023
	E-3	0.14	0.29	1.42	0.30	0.110	0.003	0.040
0.6% Mo, 0.03% Nb, no B	F	0.14	0.31	1.33	0.63	0.034	<0.0006	0.041

strength steel of 80 kg/mm² strength level, despite the reduction of its alloying elements. This is attributable to a unique combined effect caused by the addition of adequate amounts of Nb and Mo. In the case of the conventional high strength steel precipitation-hardened by use of Nb, NbC(N) has been solution-treated at a high temperature of 1200°C or above, followed by tempering after quenching the steel from the solution-treated state⁽¹⁾⁽²⁾⁽³⁾. The steel reported here is produced by the usual quenching and tempering process from a low austenitizing temperature of 900°C or thereabouts with the duplex addition of Nb and Mo. This process is interesting not only from the theoretical but also from the practical points of view in that the steel in question can be more easily manufactured than the conventional Nb-treated steel.

II. Specimens and Experiment Procedures

Table 2 gives a list of the chemical compositions of the specimens employed in tests for the mechanical properties. All of these specimens have been produced from steel ingots weighing 300 to 500 kg, cast after being melted in a high frequency electric furnace and forged into plates with a thickness of 25 mm. As the basic system, they contain 0.12~0.14%C, 0.12~0.35% Si, 1.3~1.4% Mn and 0.003~0.005% B (Steel A). They are composed of 6 systems including 10 types of steel: Steel A plus Nb (Steel B); steel A plus Mo

(Steel C); steel A with the duplex addition of Mo and Nb (Steels D-1, D-2, D-3, E-1, E-2, E-3); and steel A with the addition of Mo and Nb, but without B (Steel F).

First, their mechanical properties were examined. The heat treatment performed was; after holding the specimen at 900°C for an hour, quenching was effected in water containing 0.5% cutting oil. For tempering the in-furnace time, including the time required to raise temperature, was set at 1 hour 40 minutes (holding time: about 50 minutes) and at various temperatures of more than 600°C. JIS No. 4 test pieces were employed for the tension test, and 2 mm V-notch test pieces for the Charpy test. On the basis of the results of these experiments, the combined effect of the results of these experiments, the combined effect of Nb and Mo on the mechanical properties of steel was examined.

Next, to examine the effects of Nb and Mo on the hardenability, steel specimens shown in Tables 2, 4 and 6 were subjected to standard end-quench tests. Test specimens whose compositions are shown in Tables 4 and 6 were plates of 30-mm thickness forged from a 100 kg ingot melted in a high-frequency melting furnace. From the results of the end-quench test the effects of Nb and Mo on hardenability were studied.

III. Results of Experiments and Discussion

1. Effects of Nb and Mo on mechanical properties

Fig. 1 shows a comparison of tensile strength among the steels A, B, C and D-1. When 0.04% Nb is added to the base composition (steel B), the tensile strength increases only by 1~2 kg/mm². When 0.54% Mo is added to the base composition (steel C), the tensile

- (1) For example, GLX steel of U.S.A., FNB steel (Fuji) and YES steel (Yawata) of Japan.
- (2) S. Kanazawa, A. Nakashima and others: Lectures, Spring 1964, J.I.M.
- (3) Hotta, Muraki, Kanazawa and others: Technical Report of Fuji Iron & Steel Co., Ltd. Vol. 13, No. 3 (1964)

Fig. 1 Effect of Mo and Nb upon tensile strength.

Fig. 3 Effect of Nb% upon the tensile strength of 0.6% Mo-Nb steel.

Fig. 2 Effect of Mo and Nb upon the absorbed energy in the 2V Charpy Test.

strength goes up by 5~7.5 kg/mm². In the case of steel D-1, subjected to the duplex addition of 0.029% Nb and 0.56% Mo, the tensile strength increases by 25~32 kg/mm² as compared with the steel A. The rise in strength is far greater than the sum total of the rise by the single addition of Nb and Mo. It is noteworthy that the 80 kg/mm² tensile strength level can be obtained by combining the effects of Nb and Mo. Furthermore, according to the results of Charpy tests given in Fig. 2, steel D-1 of the Nb-Mo system is smaller in absorbed energy than steels A and B with 60 kg/mm² strength level, but has a considerably greater value than steel C whose strength level is 65 kg/mm². In terms of transition temperature of energy, $vTrE$, the steel D-1 of the Nb-Mo system indicates the most favorable tendency.

Figs. 3 and 4 give the results of examination on the effect of the Nb content on the tensile strength and toughness for the Nb-Mo system which contains 0.54~0.60% Mo. As is clear from Fig. 3, when the Nb content is more than 0.029%, an evident effect of the Nb addition was recognized. Also, according to Fig. 4, the toughness at low temperatures was the highest when the Nb content was 0.029%. From these results the Nb content of 0.03% or thereabouts is considered most optimal.

Fig. 5 indicates the tensile strength of steels of the Nb-Mo system similar to the above, when the Mo content was fixed in the neighbourhood of 0.3%, but the Nb content was changed. The tensile strength in either case stood at around 70 kg/mm² which apparently is insufficient for a high strength steel

Fig. 4 Effect of Nb% upon the absorbed energy of 0.6%Mo-Nb steel in the 2V Charpy Test.

Fig. 5 Effect of Nb% upon the tensile strength of 0.3% Mo-Nb steel.

Fig. 6 Effect of B upon the tensile strength of 0.6%Mo-0.03%Nb steel.

with 80 kg/mm² tensile strength level. From this it has become clear that when the quenching method mentioned above is adopted, the Mo addition must be at a level of 0.5~0.6%.

Figs. 6 and 7 show the effect of B on the tensile strength and toughness of steels of the Nb-Mo system with the Nb addition of 0.029~0.034% and the Mo addition of 0.56~0.63%. As to the effect of B on the tensile strength, Fig. 6 clearly shows that no appreciable effect is to be recognized. However, with respect to the toughness, as shown in Fig. 7, some effect is observed; the steel F without B is deteriorated in toughness. It may therefore be said that B is an important element in this quenching method to give an excellent quality to the heat-treated high strength steel of the Nb-Mo system.

As for the conventional high strength steel, the following formulae has been proposed by a technical research group of Ishikawajima-Harima Heavy Industries Co., Ltd., with regard to the relations between its chemical components and tensile strength or yield strength⁽⁴⁾:

$$\begin{aligned} \sigma_B(\text{kg/mm}^2) = & 94\sqrt{C} + 17\sqrt{Si} + 2\sqrt{Mn} + \sqrt{Ni} + 25\sqrt{Cr} \\ & + 15\sqrt{Mo} + 47\sqrt{V} + 70\sqrt{B} + 10\sqrt{Cu} \\ & + 1.3\frac{\sqrt{NT}}{Al \text{ sol}} - 4.2 \times 10^{-4} \frac{1}{(Al \text{ sol})^2} \\ & + 3\sqrt{Al \text{ sol}} - 11.5 \end{aligned}$$

(4) Messrs Nakamura, Naiki and Kuriyama: Ishikawajima Giho, 5(1965), 239~244.

Fig. 7 Effect of B upon the absorbed energy of 0.6%Mo-0.03%Nb steel in the 2 V Charpy Test.

Table 3 Chemical composition of steels used for the evaluation of strength in Figs. 8 and 9.

Steel	C	Si	Mn	Ni	Cr	Mo	V	B	Cu	Al sol
FTW60	0.14	0.29	1.29	0.04	0.04	0.001	0.080	0.001	0.10	0.030
FTW70	0.13	0.37	1.20	0.04	0.32	0.35	0.001	0.004	0.16	0.030
HiZ	0.15	0.25	0.87	0.76	0.48	0.39	0.045	0.004	0.32	0.030
HT100	0.17	0.35	1.22	1.40	0.99	0.82	0.072	0.004	0.18	0.032
PZ80-1	0.14	0.37	1.32	—	—	0.50	—	0.005	0.10	0.034
PZ80-2	0.12	0.31	1.32	0.67	—	0.52	—	0.004	0.10	0.042
PZ80-3	0.15	0.33	1.46	—	—	0.59	—	0.003	0.11	0.057
PZ80-4	0.12	0.27	1.43	0.61	—	0.55	—	0.004	0.11	0.041

$$\begin{aligned}
 \sigma_Y (\text{kg/mm}^2) = & 63\sqrt{C} + 22\sqrt{Si} + 2\sqrt{Mn} + 2\sqrt{Ni} \\
 & + 23\sqrt{Cr} + 19\sqrt{Mo} + 54\sqrt{V} + 98\sqrt{B} \\
 & + 16\sqrt{Cu} + 2.2\frac{\sqrt{NT}}{\text{Al sol}} - 12.0 \times 10^{-4} \\
 & \times \frac{1}{(\text{Al sol})^2} + 4\sqrt{\text{Al sol}} - 18.7
 \end{aligned}$$

Using the above formulae, the calculations of strength were made on the 10 types of steel previously shown in Table 2, the steels in actual use, such as FTW 60 to Hi-Z, shown in Table 3, and four kinds of new high strength steel of the Nb-Mo system, PZ 80, melted in a 5-ton electric arc furnace, rolled and heat-treated on the production line of the steel works. Then their calculated values were compared with those actually measured. The results thus obtained are given in Figs. 8 and 9. As is clear from the figures, the measured values for the conventional steels, FTW 70, Hi-Z and HT 100, are roughly on the 45° line, and both the measured and the calculated values agree well within the range of $\chi = \pm 0.95$.

On the other hand, all points within the rectangle of the dotted line represent Nb—0.55~0.60% Mo steels with a capacity of 80 kg/mm² strength. It should be noticed that they are located considerably higher than the 45° line. In other words, the

Fig. 8 Comparison of calculated and measured tensile strengths.

measured strength of this new Nb-Mo treated high strength steel is much higher than the calculated value according to the formulae obtained statistically from various types of conventional high strength steel. This may be ascribed, as mentioned before, to the combined effect of the Nb-Mo addition. Fig. 10 shows the result of a closer examination in this particular point.

Fig. 9 Comparison of calculated and measured yield strengths.

Fig. 10 Effect of Mo% upon the tensile strength increase caused by the coexistence of Mo and Nb.

In Fig. 10,

$\Delta\sigma_B = \sigma_B$ (actually measured value) $-\sigma_B$ (calculated value).

The effect each of Nb and Mo in respect to $\Delta\sigma_B$ thus obtained was examined. $\Delta\sigma_B$ represents the rise in strength resulting from the duplex addition of Nb and Mo. Fig. 10 indicates the relation between $\Delta\sigma_B$ and Mo%. In case of the single Mo addition, $\Delta\sigma_B$ roughly coincides with the horizontal axis within the error limit of less than 5 kg/mm². In case of the single addition of Nb, as is clear from Fig. 10, $\Delta\sigma_B$ is only 5 kg/mm² or so. On the other hand, if Nb is added together with Mo, $\Delta\sigma_B$ increases by 10–20 kg/mm² with increase in Mo content. This implies that the increase of the Mo content does not merely exercise an effect of sum total on the tensile strength of the steel, but a much greater effect, since the effect of Mo has been already included in the calculation of strength.

From the above it is clear that, when Nb is roughly 0.03% and Mo above 0.5–0.6%, a strength far higher than the calculated value is obtained due to the peculiar combined effect of the Nb-Mo addition, and that such Nb-Mo high strength steel is quite different from the conventional heat-treated steels.

2. The effect of Nb and Mo on hardenability

The combined effect of the Nb-Mo addition which affects the mechanical properties of the steel concerned is also mutually related to the hardenability. This

constitutes a major point which requires further investigation. Particularly, in the Nb-Mo treated high strength steel, there may arise the doubt whether the steel plate could be hardened to the center of the interior, since the amount of alloying elements is much reduced. The composition of this high strength steel contains B, as shown in Table 1, which gives rise to a complicated effect on hardenability. First, for the sake of simplification it has been examined whether there is any effect of the Nb-Mo addition on hardenability when B is not contained. For this purpose, an end-quench test has been made by using the same kind of steel as shown in Table 4. From the result so obtained and also from the composition shown in Table 4, the value of f_{Nb} , the multiplying factor of Nb, was calculated by taking it as an unknown quantity. The numerical value of f_{Nb} was calculated from the equation $D_I = D_{IC} \cdot f_{Si} \cdot f_{Mo} \cdot f_{Nb}$ ⁽⁵⁾, where D_I was obtained from the Jominy curve, while on the right side excepting f_{Nb} the known multiplying factors in hardenability of the respective elements were substituted therefore⁽⁶⁾. As a result of this calculation, it may be said that, if the multiplying factor in hardenability of Nb is to become unusually large only in the case of its coexistence with Mo, there does exist the Nb-Mo duplex addition effect on hardenability. The results of the end-quench test are given in Fig. 11, and the result of calculation for the multiplying factor in hardenability of Nb is shown in Table 5. In the numerical value of f_{Nb} in Table 5, the values for steels A and C cannot be those of f_{Nb} , because these types of steel do not contain Nb and therefore should become 1. Therefore, they are represented by (f_x) and the fact that they do not become exactly 1 is presumably due to an experimental error. However, when the steel B is compared with the steel D in respect to f_{Nb} or the multiplying factor in hardenability of Nb by taking into account the extent of such an error, there will be no difference between the two steels. In other

Fig. 11 Jominy curves of steel shown in Table 4. No boron is contained in these steels.

(5) S. Owaku: *Hardenability* (1956), p. 62.

(6) S. Owaku: *Hardenability* (1956), p. 151.

Table 4 Chemical composition of steel used for the evaluation of hardenability.

Steel	C	Si	Mn	P	S	Cu	Ni	Mo	Nb	Al sol	Al insol	N sol	N insol	B
a	0.16	0.36	1.36	0.013	0.015	0.11	0.029	0.007	<0.002	0.040	0.002	0.0162	<0.001	<0.0005
b	0.17	0.50	1.44	0.010	0.013	0.11	0.043	0.007	0.037	0.036	0.003	0.0157	<0.001	<0.0005
c	0.15	0.33	1.39	0.012	0.012	0.10	0.030	0.61	<0.002	0.046	0.005	0.0199	<0.001	<0.0005
d	0.16	0.37	1.44	0.012	0.005	0.11	0.034	0.60	0.038	0.019	0.003	0.0202	0.0011	<0.0005

Table 5 Effect of the co-existence of Nb and Mo upon hardenability.

Steel		D_I from Jominy curve	D_{IC}	$\frac{D_{IC} \cdot f_{Si} \cdot f_{Mn}}{f_{Mo}}$	f_{Nb}
a	Base	1.04	0.123	0.90	(f_x) 1.16
b	Nb	1.03	0.127	1.07	0.96
c	Mo	2.60	0.120	2.49	(f_x) 1.05
d	Nb-Mo	2.78	0.123	2.70	1.03

Fig. 12 Multiplication factor of Nb (by Kramer et al.⁽⁷⁾).

Fig. 13 Jominy curves of steels shown in Table 2. Boron treated.

words, in the case of the steel which does not contain B, no particular effect of Nb-Mo combination on hardenability has been observed. Furthermore, it has been found that the multiplying factor in hardenability of Nb is not greatly different from that given in Fig. 12, regardless of Mo addition⁽⁷⁾ and that it is nearly equal to 1 when Nb is at a level of 0.03%.

Now, what comes next for discussion is the effect of the Nb-Mo duplex addition on hardenability for the Nb-Mo high strength steel containing B. The results of end-quench tests for the steels B, C and D-1 are given in Fig. 13. When the results of Fig. 13 on the steels containing B are compared with those

of Fig. 11 on the steels not containing B, it is noticed that there is a difference in hardenability between the steels produced with the Mo single addition and the Nb-Mo duplex addition. In other words, when B is not contained, the multiplying factor in hardenability of Nb approximates 1, and accordingly the hardenability curves in cases of the Mo single addition and the Nb-Mo duplex addition coincide with each other. However, when B is contained, if Nb and Mo are coexistent, its hardenability curve lies considerably upward, and the hardenability is remarkably increased in comparison with that in the case of Mo being added singly. From the above it may be inferred that this is either due to the simple effect of B itself or to the combination effect of the Nb-Mo duplex addition in the presence of B. In order to examine this point as accurately as possible, we have made a calculation of hardenability which enables us to take into due consideration the quantitative variation of other alloying elements. An example of the results is as follows:

Standard end-quench tests were made for steels with B sol made constant as shown in Table 6 (100 kg steel ingots completely killed with aluminum after being melted in a high frequency induction furnace and

Table 6 Effect of the co-existence of Nb and Mo upon the multiplication factor of B.

Steel	C	Si	Mn	Mo	Nb	B sol	B insol	D_I	f_B
e	0.13	0.21	1.31	0.54	<0.002	0.0007	0.0022	2.66	1.40
f	0.14	0.29	1.49	0.56	0.029	0.0007	0.0021	4.67	1.92
g	0.13	0.30	1.35	0.006	0.040	0.0008	0.0034	1.15	1.45

forged into a plate 30 mm in thickness). Following a similar procedure to the above, f_B , the multiplying factor in hardenability of B, was determined. In so doing, f_{Nb} , the multiplying factor of Nb, was taken as 1 on the basis of the results shown in Table 5. Results of the calculation are given in the extreme right column of Table 6. According to them, it is clear that the multiplying factor in hardenability of B considerably increases by the duplex addition of Nb-Mo. Only one example of the results is given in Table 6, but a similar tendency has been proved obtainable with full reproducibility. The calculation of Table 6 has been done on the assumption that the hardenability increase only by B is effected. In reality, however, the combination effect of the Nb-Mo-B tripple addition is thought to be exercised. It may be said, therefore, that in this new type of Nb-Mo high strength steel, the good hardenability sufficient for practical use is assured by the tripple addition of Nb-Mo-B, in spite of the reduction in alloying elements

(7) Kramer, Hafner & Toleman: Trans. AIME, 64 (1944), 667.

from the conventional steel. However, the superior weldability of this new steel is guaranteed for the following reasons. The hardenability of this steel when austenitized at 900°C is a little lower than that of conventional steel as is apparent from Fig. 13. Moreover, since this new type of steel contains (Nb Mo) C which is hardly dissolvable into matrix, the dissolution of chemical components of this steel is little at the weld heat affected zone where the holding time at high temperatures is very short. Therefore, there is a tendency that the hardenability of heat affected zone is rather lower than that of conventional steels. Thus, the good weldability of this steel is effected.

IV. Summary

In the heat-treated high strength steel of the Nb-Mo system developed as the 80 kg/mm² strength steel, the alloying elements are considerably reduced in number and quantity as compared with the conventional T-1 type high strength steels, and the resulting reduction in what is called carbon equivalent in welding contributes to the improvement in weldability. Another characteristic of the steel is that, in spite of this reduction of the alloying elements, it can maintain a sufficient strength and toughness as high strength steel with 80 kg/mm² strength level by the ordinary quenching from about 900°C and a subsequent tempering process, instead of the conventional solution treatment at high temperatures and direct quenching. This is to be ascribed to the special effect produced by the duplex addition of Nb and Mo. In this paper is reported the results of research conducted on the effect of such a duplex addition of Nb and Mo upon the mechanical properties and hardenability of the steels concerned. As the result of experiments the

following facts have been disclosed:

(1) In the case of the steel with the simultaneous addition of 0.029% Nb and 0.56% Mo after quenching from 900°C and tempering at 600~650°C, the rise in strength is by far greater than the effect calculated in terms of the sum total of the rise in strength obtained, respectively, by the single addition of Nb and Mo. This is considered to be the combined effect of the Nb-Mo addition.

(2) When both strength and toughness are taken into account, the optimum Nb content should be at 0.03% or thereabouts, and the Mo content is required to be at 0.5~0.6% or above.

(3) In the case of Nb-Mo high strength steel with 80 kg/mm² strength level, the addition of B is important for securing excellent toughness.

(4) This new Nb-Mo heat-treated high strength steel has a greater strength by about 20 kg/mm² than that estimated from the past knowledge on chemical components and strength of steels.

(5) There is no more rise in strength due to the combined effect of Nb-Mo addition, when the Nb content is increased to more than 0.03%. However, the effect of increase in Mo content is greater than that calculated in terms of the arithmetic addition, and the effect is greater with increasing Mo content.

(6) In case B is not contained in the steel, examination has been carried out as to whether there is any combined effect of the Nb-Mo duplex addition on the hardenability of this steel, but no particular duplex effect has been observed.

(7) In case B is contained in the steel, it has been revealed that the hardenability of this steel increases by the combined effect of the Nb-Mo-B tripple addition.