590MPa Class Fire-Resistant Steel for Building Structural Use

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Abstract

The requirement for fire-resistant with higher strength has increasingly prevailed as high strength structural steels have been evolving in accordance with development of higher and larger scale of building. The effects of alloying elements and microstructure on high temperature-strength were studied and basic properties of newly developed 590MPa class of fire-resistant structural steels, which possess 590MPa class of tensile strength at room temperature, high resistivity against softening at 600°C (873K), and sufficient toughness in HAZ, were briefly described.

1. Introduction

Fire-resistant steel for building structural use, which Nippon Steel Corporation developed in 1988 for the first time in the world, is characterized by markedly enhanced fire-resistance properties such as high-temperature strength. Presently it is widely used for structures such as drive-in multi-level car parking, roof frames for atria and sports facilities like gymnastic halls. One of the most important characteristics of fire-resistant steel is that its yield strength at 600°C (873K) is 2/3 or more of the specified minimum yield strength at room temperature. By virtue of its good high-temperature properties, fire-resistant steel has made it possible to reduce or eliminate fire-resistant coating for steel frames, which was compulsory under the Building Standard Law in the past, and as a result, significantly reduced building construction costs and period, and facilitated attractive building design.

In the meantime, as the height and size of buildings grew larger and larger in Japan, Nippon Steel actively responded to demands for higher strength of building structural steels. For example, the 590 MPa class steel having the standard authorization (denomination) of SA440 (Nippon Steel's trade name BT-HT440), which was approved in 1996 by the then Minister of Construction (now, the Minister of Land, Infrastructure and Transport) for general building application, has been widely used mainly for high-rise buildings and large-span

structures. While the strength of steel for general building structural use increased to as high as 590 MPa, the tensile strength of fire-resistant steel was raised only to the level of 520 MPa.

However, as the application of 590 MPa class steel expanded over the last years, demands for fire-resistant steel with the same level of strength increased. In view of this, on the basis of the long-accumulated technologies and know-how for the production of fire-resistant and high-strength steels, Nippon Steel has developed an innovative 590 MPa class fire-resistant steel for building structural use (Nippon Steel's trade name BT-HT440-FR), which has both a 590 MPa class strength at room temperature and excellent high-temperature properties. This paper explains, in the first place, the concept of the development of the new fire-resistant steel and the results of basic studies on the mechanism of high-temperature strength and, then, briefly presents the performance in actual application of the developed steel test produced on commercial facilities.

2. Definition of Development Targets

The object in the development of the new fire-resistant steel was to realize a better high-temperature strength on the basis of SA440 (BT-HT440) while maintaining the properties of high strength and low yield ratio (YR ≤ 80%). For this end, the following targets were defined for the project: the chemical composition, the basic properties of base metal such as strength and toughness and the weldability

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Table 1 Specifications of BT-HT440 steels

Chemical compositions

Specification	Chemical compositions (mass %)				
	C	Si	Mn	P	S
BT-HT440B	≤ 0.18	≤ 0.55	≤ 1.60	≤ 0.030	≤ 0.020
BT-HT440C					≤ 0.008

P_{cm} (chemical composition for susceptibility of crack in welding)

Specification	Thickness(mm)	P_{cm}(%)
BT-HT440B	≤ 40	≤ 0.28
BT-HT440C	40 <	≤ 0.30

Mechanical properties

Spcecifation	Thickness	YP or YS	TS	YR	EL*	$_vE_0$	RAz
	(mm)	(MPa)	(MPa)	(%)	(%)	(J)	(%)
BT-HT440B	19 ≤	440 ≤	590 ≤	≤ 80	20 ≤	Av. ≥ 47	-
BT-HT440C	≤ 100	≤ 540	≤ 740		(26 ≤)		≤ 25

*JIS Z 2201 No.4 test piece, No.5 test piece in parentheses

YP: yield point, YS: yield strength, TS: tensile strength, YR: yield ratio,

EL: elongation, RAz: reduction of area

of the steel should be the same as those of SA440 (see **Table 1**); and the yield stress (0.2% offset strength) at 600˚C should be 2/3 or more of the specified minimum yield strength (440 MPa) at room temperature, i.e., 295 MPa or more.

3. Production Method of Low-Yield-Ratio High-Strength Steel

It has been known that a mixed structure of bainite and ferrite is effective in achieving a low yield ratio (YR) with high-strength steel, and that a volume fraction of ferrite equal to or more than 20% stably satisfies a low YR of 80% or less[1]. A direct lamellarizing and tempering (DL-T) process or a direct quenching, lamellarizing and tempering (DQ-L-T) process is employed to obtain the mixed structure of bainite and ferrite. In the former steel are cooled by water from a temperature range equal to or below the Ar_3 transformation temperature (γ / α dual-phase region) in an on-line accelerated cooling facility, and in the latter steels are directly quenched from a temperature range equal to or above the Ar_3 transformation temperature (γ single-phase region) in an on-line accelerated cooling facility and then lamellarized in an off-line heat treatment facility, that is steels are heated up to the γ / α dual-phase region between the Ac_1 and Ac_3 transformation temperatures followed by water cooling. Whereas the former has an advantage that the off-line L treatment can be omitted, the latter has an advantage that the structure of a thick material, in which temperature difference in the thickness direction tends to be large especially in the on-line treatment, can be robustly controlled. With respect to the importance of stable structure and material quality of thick plates, the DQ-L-T process was decided to be adopted for the new steel product.

4. Study on Mechanism for High-Temperature Strength of Fire-Resistant Steel

It is most important to quantitatively clarify the mechanism to enhance the high temperature strength of steels in innovatively improving the high-temperature strength. Firstly the temperature dependence of yield strength was analyzed by formulating the temperature dependence and comparing the high-temperature strengths

of 490-MPa-class of ordinary steel and fire-resistant steel. The results of the basic studies on the mechanism for high-temperature strength are described below.

4.1 Formulation of temperature dependence of yield strength

It is generally understood that plastic deformation occurs when dislocations are activated by external stress or thermal energy to a level to overcome the resistance imposed by obstacles such as grain boundaries, dislocation forests, solute elements, and precipitates, and as a consequence, continuously move in a crystal. This means that, if the strain rate of a material can be expressed in terms of dislocation motion and, further, the dependence on external stress and temperature of the activation energy required for dislocations motion can be calculated, then it becomes possible to formulate the relationship among strain rate, stress and temperature.

The shear strain rate and the velocity of dislocation motion in a metal crystal such as steels are expressed as follows, respectively[2]:

$$\dot{\gamma} = \rho bv \tag{1}$$

$$v = v_0 \exp\left(-\frac{Q(\tau_{th}, T)}{kT}\right) \tag{2}$$

in which:

$\dot{\gamma}$ is shear strain rate;

ρ is the density of the dislocations that contribute to deformation;

b is the Burgers vector; and

v is the average velocity of dislocations in a crystal.

Based on the above equations and $\dot{\gamma}_0 = \rho bv_0$, the following equation for shear strain rate is obtained:

$$\dot{\gamma}(\tau_{th}, T) = \dot{\gamma}_0 \exp\left(-\frac{Q(\tau_{th}, T)}{kT}\right) \tag{3}$$

in which:

τ_{th} is thermal (temperature-dependent) stress or effective stress;

T is temperature in Kelvin;

$Q(\tau_{th}, T)$ is the activation energy at temperature T (K) under a thermal stress of τ_{th};

$\dot{\gamma}(\tau_{th}, T)$ is the shear strain rate at temperature T (K) under a thermal stress of τ_{th}; and

$\dot{\gamma}_0$ is the shear strain rate in the region where thermal (internal) stress is 0, namely short-range resistance is 0, which is nearly equal to maximum strain rate.

In the meantime, the following phenomenological equation has been deduced for the stress dependence of the activation energy of the dislocation motions against a short-range resistance[3]:

$$Q(\tau_{th}, T) = Q_c(T)\left[1 - \left(\frac{\tau_{th}}{\tau_0}\right)^P\right]^q \tag{4}$$

in which:

$Q_c(T)$ is the activation energy at temperature T (K) under a thermal stress τ_{th} of 0;

τ_0 is the thermal stress at 0 K (maximum internal stress), which is nearly equal to the stress under an activation energy $Q(\tau_{th}, 0)$ of 0; and

p and q are the parameters that express the profile of the activation energy (p, q > 0).

When the temperature dependence of the shear modulus, which is very small, is neglected for the simplicity and the temperature (K) at which the thermal stress τ_{th} is 0 is expressed as T_c, equations (3) and (4) yield the following equation:

$$\tau = \tau_0 \left[1 - \left(\frac{T}{T_c} \right)^{1/q} \right]^{1/p} + \tau_{ath} \qquad (5)$$

provided,

$$T_c = \frac{Q_c(T)}{k \ln\left(\dfrac{\dot{\gamma}_0}{\dot{\gamma}(\tau_{th}, T)} \right)} \qquad (6)$$

in which:

τ is external stress; and

τ_{ath} is athermal (non-temperature-dependent) stress or internal stress.

It has been known theoretically that the values of p and q in equations (4) and (5) are within the ranges of $0 < p \le 1$ and $1 \le q \le 2$ with respect to various sources of short-range resistance[2]. Supposed that the respective medians, namely $p = 1/2$ and $q = 3/2$, give an appropriate approximation for all possible cases, the following equation is deduced:

$$\tau = \tau_0 \left[1 - \left(\frac{T}{T_c} \right)^{2/3} \right]^2 + \tau_{ath} = \tau_0 \cdot f(T) + \tau_{ath} \qquad (7)$$

Thus, it is possible to evaluate thermal (τ_{th}) component and athermal component (τ_{ath}) of yield stress, using equation (7) and calculating the dependence of yield stress on the parameter $f(T) = \left[1 - \left(T / T_c \right)^{2/3} \right]^2$.

4.2 Discussion on thermal and athermal stresses on fire-resistant steel and ordinary carbon steel

Fig.1 shows the comparison of the 490-MPa-class ordinary steel and fire-resistant steel having the chemical compositions shown in **Table 2** in terms of the temperature-dependent change of YS ratio (= yield strength at high temperatures/yield strength at room tempera-
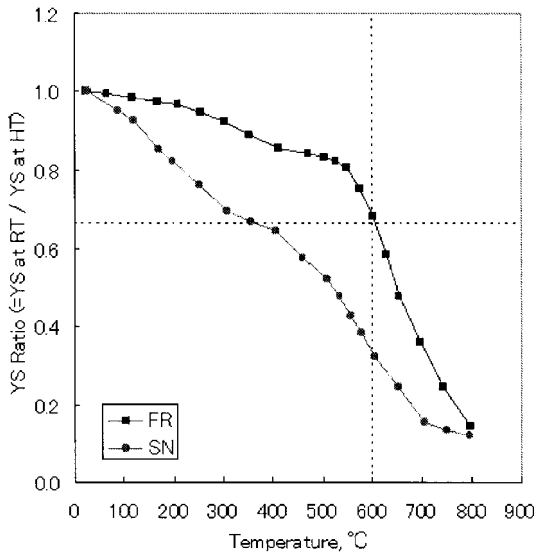
ture) over a temperature range from room temperature to 900°C. Whereas the YS ratio of the ordinary carbon steel decreases substantially linearly as temperature rises, the decrease in that of the fire-resistant steel is smaller up to roughly 500 to 600°C. Then, the thermal component (τ_{th}) and athermal component (τ_{ath}) of YS ratio are evaluated using equation (7) as shown in **Fig. 2** and **Table 3**. The
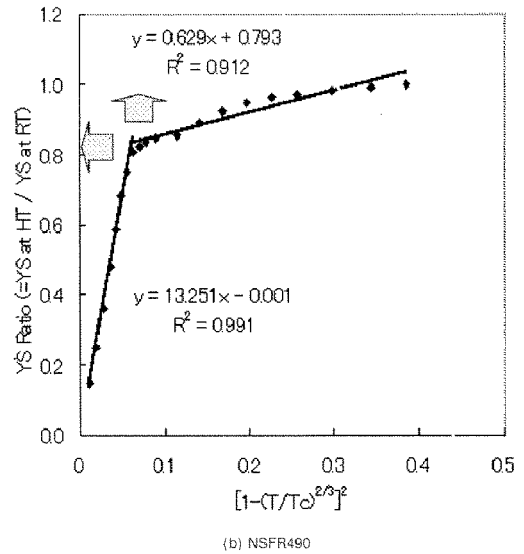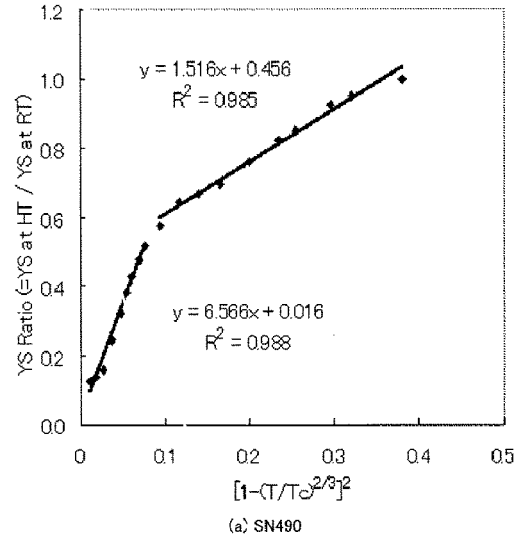

(a) SN490

(b) NSFR490

Fig. 2 Determination of parameter of temperature dependence of yield strength

Fig. 1 Temperature dependence of yield strength ratio in SN 490 and NS FR 490 steels

Table 2 Chemical compositions (mass%)

Steel	C	Si	Mn	P	S	Al	Mo	Nb	P_{cm}	C_{eq}
NSFR490	0.11	0.24	1.12	0.007	0.002	0.02	0.51	0.02	0.20	0.43
SN490	0.16	0.30	1.30	0.008	0.003	0.03	-	-	0.24	0.39

Table 3 Parameter of temperature dependence of YS ratio in SM 490 and NS FR 490

		SN 490	NSFR490
Critical temperature T_c (°C)		600	900
Transition Temperature(°C)		450	550
Low-temperature region	τ_0	1.516	0.629
	τ_{ath}	0.546	0.7931
High-temperature region	τ_0	6.566	3.251
	τ_{ath}	0.016	– 0.001

temperature dependence of YS in the low-temperature region (f(T) > 0.1) is remarkably different in the high-temperature region (f(T) < 0.05) between two of the steels. The transition from the low- to high-temperature regions of the fire-resistant steel (roughly 550°C: f(T) ≈ 0.064) occurs at higher temperature than that of the ordinary steel (roughly 450°C: f(T) ≈ 0.073), and in addition, the temperature dependence of the YS ratio of the fire-resistant steel is significantly small in the low-temperature region, and the influence of athermal component is found to be dominant.

The athermal component is considered to be determined by long-range resistance to the slip motion of dislocations. The primary sources of such long-range resistance are grain boundaries and dislocation forests. Considered that the transition between the low- and high-temperature regions is observed even with the ordinary steels and that the ordinary steels do not contain any alloying elements forming carbonitride precipitates such as Nb and Mo, the decrease in the athermal component of the ordinary steel in high temperatures occurs as a result of the recovery of dislocations by climb motion and annihilation, recrystallization and the significant decrease in dislocation forest density. In other words, if the difference in the temperature dependence of yield strength between the low- and high-temperature regions is due to the difference in dislocation density between the temperature regions, then the retardation of dislocation recovery around the transition temperature is supposed to cause the shift of the transition temperature between the low- and high-temperature regions to a higher temperature, which is observed in the fire-resistant steel.

It is widely known that solute Mo and Nb have effects of retarding the climb motion and recovery of dislocations as well as grain boundary migration. Thus, the expansion of the low-temperature region (the region in which the temperature dependence of yield strength is low) of fire-resistant steel to the high-temperature side is inferred to result from the effect of these solute elements of retarding dislocation recovery. Further, the fact that the temperature dependence of yield strength of the fire-resistant steel becomes low in the low-temperature region indicates that there is another source of long-range resistance in addition to grain boundaries and dislocation forests, and the stress field resulting from coherent/semi-coherent strain of dispersed precipitates is suspected to be the source of long-range resistance. The mechanism of precipitation hardening using coherent/semi-coherent particles is basically the same as that of solid solution strengthening, but the stress field resulting from the coherent/semi-coherent precipitates is far stronger than that resulting from solid solution, and the range affecting the dislocation motion is greater as well.

Observations with a transmission electron microscope (TEM) or atom probe field ion microscope (AP-FIM) have confirmed that complex carbonitride of Mo, Nb and V (Nb, Mo, V)(C, N) form coherent/semi-coherent precipitates in fire-resistant steel[4]. For this reason, it is inferred that the reason why the athermal component of fire-resistant steel increases in the low-temperature region is that the misfit stress resulting from the coherent/semi-coherent strain acts as a long-range resistance to dislocation motion.

4.3 Study on composition of complex carbonitride

As mentioned above, the mechanism of high-temperature strength in combined-Mo-Nb-addition type fire-resistant steel works as a result of the following sequence: retardation of dislocation recovery by solute Mo and Nb and consequent prevention of the decrease in dislocation density; introduction of coherent/semi-coherent strain resulting from the precipitation of complex carbonitride of Mo and

Nb; and as a consequence to these, the significant increase in long-range resistance to dislocation motion in the temperature range up to 550°C. Therefore, if it is possible to estimate the state of Mo and Nb in steel, that is, whether they are in solid solution or precipitate, that will provide a guideline useful for determining the compositions of the elements most appropriate for maximizing high-temperature strength.

An equilibrium calculation using the thermodynamic software ThermoCalc is effective as a method of such estimation. The trials of studies using ThermoCalc are explained in the following section. In relation to the studies, the studies on equilibrium composition of (Nb, Mo)(C, N) at 600°C with the chemical composition of the 490-MPa-class fire-resistant steel shown in Table 2 reveals that the predicted Mo/Nb ratio by thermodynamic calculation is slightly higher than that observed in the TEM analysis on the composition of complex carbonitride of Mo and Nb of the same steel after a long-period retention at 600°C In this point of view, the SSOL database is modified with respect to the free energy of Mo for its dissolution in complex carbonitride of Nb, Mo and V (MC) in accordance with the analysis result, and used for the studies explained below.

5. Studies on Optimum Mo Addition Amount and Appropriate Microstructure

5.1 Influence of Mo addition amount on high-temperature strength

Nb is an alloying element effective in increasing high-temperature strength as well as Mo, however, since Nb forms carbonitride at higher temperatures than Mo does, it tends to form coarse particles. When the addition amount of Nb is 0.03 wt. % or more, the toughness of a welding heat affected zone (HAZ), in particular, may be markedly deteriorated. From this point of view, the addition amount of Nb of the new steel is set from 0.02 to 0.03 wt. %, and on this basis, the necessary amount of Mo to achieve aiming high-temperature strength is attempted to be specified.

Using laboratory equipment, the specimens of steels with chemical compositions and strengths at room temperature and 600°C within respective ranges as shown in **Table 4** were prepared. **Fig. 3** shows the relationship between the Mo addition amount and the YS ratio at 600°C of these test-produced steels. High-temperature YS ratio increased as the addition amount of Mo increased, but the fluctuation of the YS ratio was very large. From preliminary evaluation it was expected to be necessary to add Mo by more than 1.0 wt. % for robustly obtaining a YS ratio of 2/3 or more at 600°C. In order to opti-

Table 4 Chemical compositions of Mo/Nb added steels (mass%)

	C	Si	Mn	Mo	Nb	V	Ti	Al	P_{cm}	C_{eq}
Ave.	0.05	0.14	0.78	0.85	0.04	0.06	0.01	0.01	0.16	0.40
Max.	0.13	0.40	1.62	1.49	0.13	0.24	0.10	0.04	0.25	0.59
Min.	0.00	0.03	0.19	0.00	0.00	0.00	0.00	0.00	0.08	0.10

Tensile properties at room temperature and 600°C

	Room temperature properties			YS at 600°C	YS Ratio
	YS(MPa)	TS(MPa)	YR(%)	(MPa)	(600°C/room temp.)
	325	490		217	(%)
	445	610	80		
Ave.	388	527	73.5	279	72.5
Max.	570	706	96.8	425	92.1
Min.	207	354	58.5	128	34.3

$y = 1.09E+01x + 6.29E+01$
$R^2 = 9.41E-02$
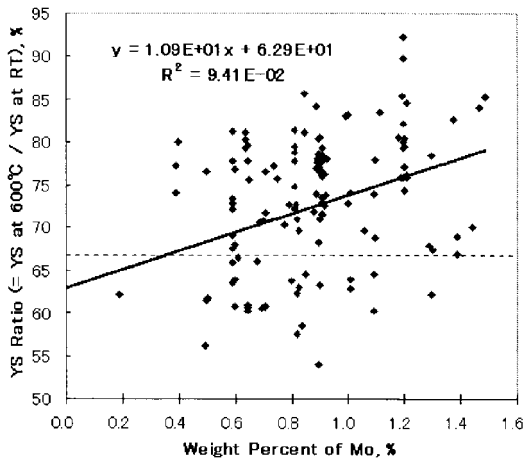
Fig. 3 Effect of Mo content on YS ratio at 600°C

Fig. 4 YS ratio at 600°C/700°C with various microstructure and volume fraction of MC

mize the chemical composition of the fire-resistant steel to be developed, it was thought to be necessary to analyze influencing factors of high-temperature strength in more detail.

5.2 Influence of microstructure of matrix

The microstructure of matrix has significant influence on parameters such as initial dislocation density at high temperatures. Thus, the relationship between high-temperature YS ratios of various microstructures of and the equilibrium formation of MC was examined, using ThermoCalc and the modified SSOL database, as shown in **Fig. 4**. With the same level of Mo addition amount, a bainite (B) or bainite + small-fraction ferrite (F) structure showed the highest high-temperature YS ratio, followed by ferrite + small-fraction bainite and ferrite + pearlite (P) structures, in this order; thus it became clear that a bainitic structure was the most effective in enhancing high-temperature strength. The result that bainite, which is a structure having a high dislocation density, is effective in enhancing and stabilizing high-temperature strength agrees well with the presumption mentioned earlier that the high-temperature strength at 600°C results from the mechanism activated by solute Mo and Nb for retarding dislocation recovery.

In addition, since it is considered necessary that the matrix consists of a certain fraction of soft ferritic structure to achieve the low yield ratio (YR) required for steels of building structural use, the matrix will have to be of a bainite + small-fraction ferrite or ferrite + small-fraction bainite structure. In order to secure a YS ratio of 2/3 or more robustly at 600°C with the above structure, it is necessary from Fig. 4 that the fraction of MC precipitate should be roughly 4.5 × 10⁻³ or more.

5.3 Influence of MC fraction and solute Mo

Using ThermoCalc and the modified thermodynamic database, the amount of the metastable equilibrium formation of MC precipitate at 600°C (in volume fraction), the amount of solute Mo in a BCC phase were calculated. **Fig. 5** shows the relationship among them and the YS ratio at 600°C. The diagram shows that high-temperature YS ratio increases as the volume fraction of MC precipitate and the solute Mo amount increase.

5.4 Relationship between Mo addition amount, MC fraction and solute Mo

Lastly, using ThermoCalc, the amount of the metastable formation of MC and the amount of solute Mo in the BCC phase of 0.09C-
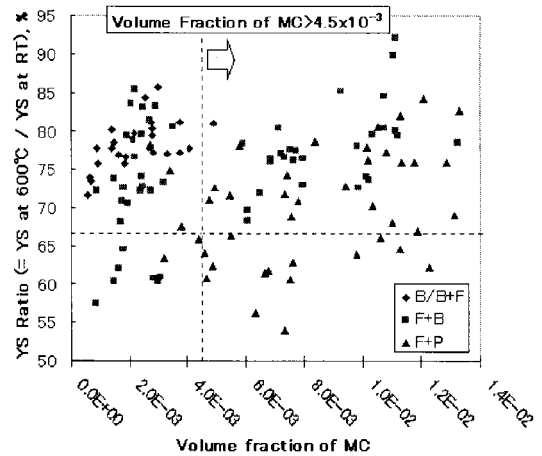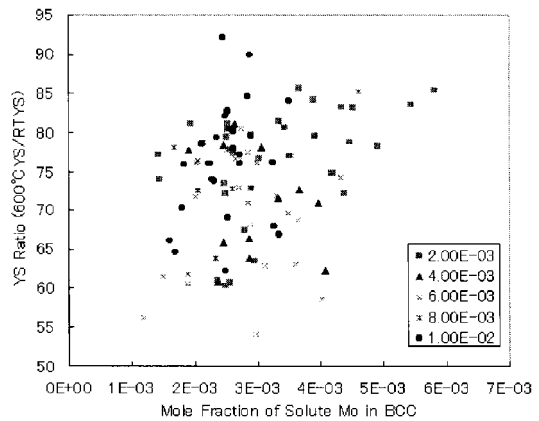

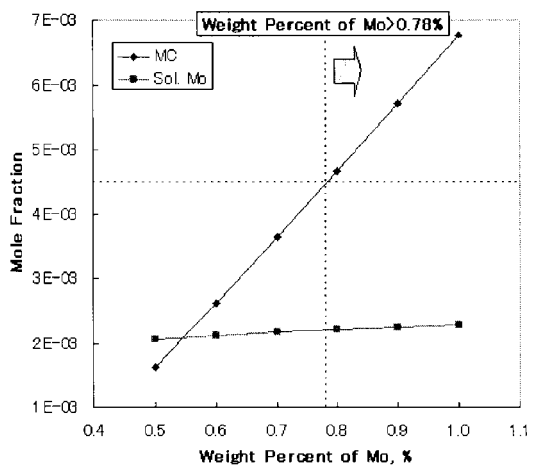Fig. 5 Effect of mole fraction of solute Mo and volume fraction of MC on YS ratio at 600°C

Fig. 6 Mole fraction of MC and solute Mo as a function of weight percent of Mo

1.25Mn-0.25Si-0.004N steel at 600°C were calculated with various amounts of Mo addition from 0.5 to 1.0 wt. %. **Fig. 6** shows the result. It is understood from the diagram that the amount of meta-stable formation of MC and the solute Mo in the BCC phase increase monotonously as the addition amount of Mo increases. From Fig. 6, with a bainite + small-fraction ferrite or ferrite + small-fraction bainite structure, 0.78 wt. % seems to be the lower limit of the Mo addition amount for making the amount of the metastable equilibrium formation of MC precipitate exceed 4.5×10^{-3}, the least required MC fraction for raising the YS ratio at 600°C robustly to 2/3 or more.

6. Characteristics of Steel Test Produced on Commercial Facilities

6.1 Chemical composition and production process conditions

Table 5 and **Fig. 7** summarize the concept of the development of the 590 MPa class fire-resistant steel for building structural use based on the studies described above. The properties of the steels newly developed and manufactured on the actual production line, with the guidelines delineated therein, are briefly described: steel having the chemical composition shown in **Table 6** was melted in a 300 t converter and cast into 240 mm thick slabs on a continuous caster; the

Table 5 Concept of 590MPa class of fire resistant steel

| Specifications			Target	Concept	Conventional 490MPa (NSFR490)
SA440	Strength	YS	440/540MPa	Bainite / ferrite microstrucuture	Ferrite / pearlite microstructure
		TS	590/740MPa		
	YR		≤ 80%		
	Toughness $_vE_0$		≥ 47J		
	Elongation		≥ 20%		
YS at high temperature	600°C		≥ 295MPa (2/3 of lower limit of YS at room temperature (440MPa))	(1) Retardation of dislocation recovery due to solute Mo or Nb, (2) Coherent / semi-coherent dispersion strengthening due to carbo-nitride of Nb and Mo	Coherent / semi-coherent dispersion strengthening due to carbo-nitride of Nb and Mo
Weldability				Lower carbon content	Limitation of Nb and Mo amount
Robustness of production			Same as conventional SA440 Same as conventional SA440	DQ(direct quenching)-L(lamellarizing) -T(tempering)	Controlled rolling (CR)
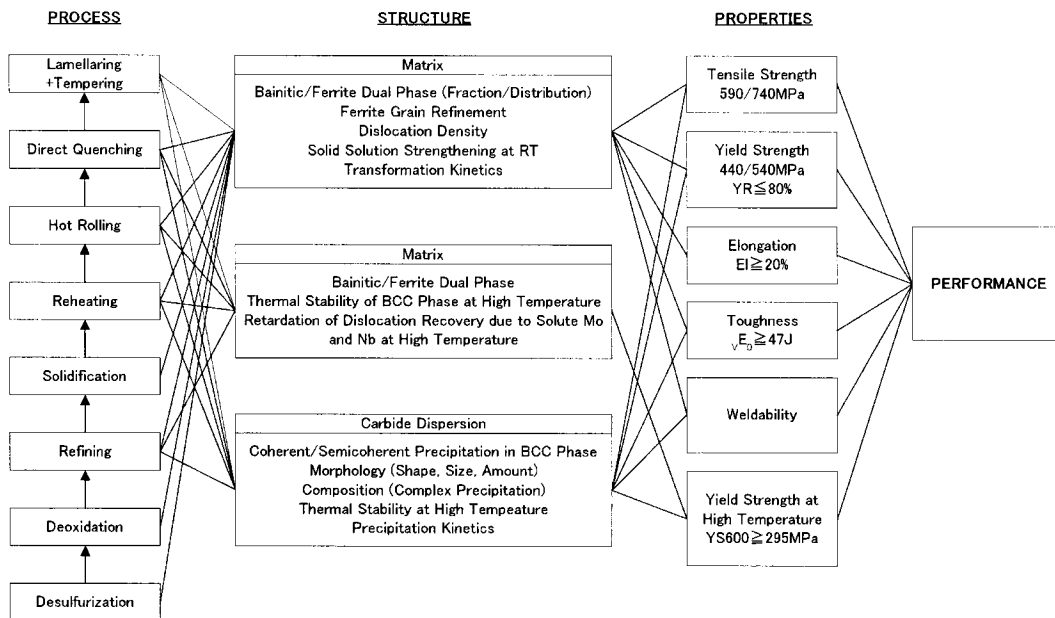
Fig. 7 System chart of 590MPa fire resistant steel

Table 6 Chemical compositions of 590MPa fire resistant steel (mass%)

Steel	C	Si	Mn	P	S	Cr	Mo	Nb	P_{cm}	C_{eq}
BT-HT440C-FR	0.09	0.28	1.24	0.006	0.0015	0.18	0.78	0.02	0.22	0.53

slabs were reheated to 1,100 to 1,150˚C and rolled into 36, 60 and 85 mm thick plates at a finish rolling temperature of 900 to 950˚C; and the plates were subjected to direct quenching (DQ) by accelerated cooling, which was followed by a dual-phase, or lamellarizing (L), heat treatment and tempering (T). The properties of the test-produced steel plates are explained below.

6.2 Fundamental properties of base metal

Photo 1 is an optical photomicrograph of the base metal of the developed steel. A mixed structure of bainite and ferrite was obtained as envisaged.

Table 7 shows the mechanical properties of the base metal. The strength at room temperature was well above the specified value of SA440, and YR, a parameter of seismic performance, was as low as less than 80%. The absorbed energy in Charpy impact test at 0˚C was as good as 100 J or more. The hardness distribution in the thickness direction (not shown in the table) was satisfactory: the maximum hardness was HV 230 and the fluctuation range was roughly HV 40.

6.3 Weldability and performance of welded joints

Fig. 8 shows the results of y-slit restraint cracking test of welded joints of the test-produced 590 MPa class fire-resistant steel. No weld cracking was observed at the test also at room temperature. The maximum hardness of HAZs was roughly HV 300, evidencing good weldability. This is because large amounts of Nb and Mo in combination were added to the fire-resistance steel and, on the other hand, the amounts of C and Mn were reduced, and as a result, the chemical
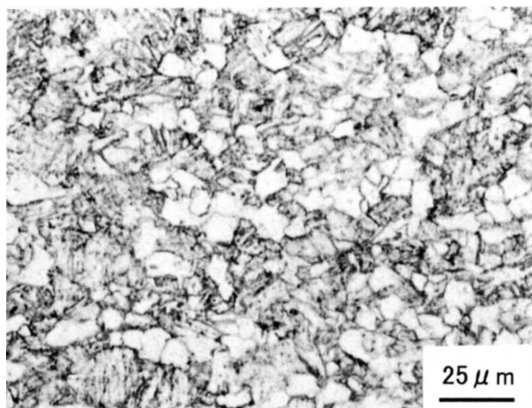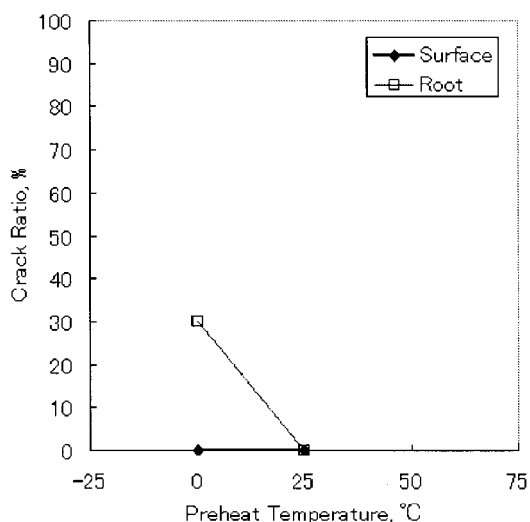

Fig. 8 y-slit restraint cracking test

composition for susceptibility to welding crack P_{cm}, an index of weldability, was controlled to a low level. **Table 8** shows the properties of various kinds of welded joints employed in building structures. The specimen joints were prepared by manual welding (SMAW) at a low heat input, submerged arc welding (SAW) at an intermediate heat input and SESNET welding at a very high heat input, and their mechanical properties were tested. All the specimens showed good strength at room temperature and 600˚C. The Charpy absorbed energy values at 0˚C in welding fusion line and heat affected zones (FL and HAZ) and weld metal (WM) were good up to a heat input of 44 kJ/mm by SAW. The performance of the joints by the SESNET welding at a very high heat input was in the same level as that of conventional ordinary steel.

7. Summary

The temperature dependence of yield strength has been formulated, and the followings have been clarified:

The mechanism of the high-temperature strength of combined-Mo-Nb-addition type fire-resistant steel works approximately as a result of (i) the effects of solute Mo and Nb of retarding the recovery of dislocations and the decrease in dislocation density and (ii) the introduction of coherent/semi-coherent strain resulting from the pre-

Photo 1　Optical micrograph of tested steel (thickness:60mm,1/4 thickness)

Table 7　Mechanical properties of tested steels

Thickness (mm)	Direction L: Longitudinal T: Transverse	Tensile test at room temperature (1/4t)				Tensile test at 600°C			Charpy test	
		YP (MPa)	TS (MPa)	El (%)	YR (%)	YP(YS) (MPa)	TS (MPa)	El (%)	$_vE_0$ Min./Av. (J)	$_vT_{rs}$ (°C)
Target		440/540	590/740	≥ 20	≤ 80	≥ 295	-	-	Av.≥ 47	-
36	L	508	673	29	75	-	-	-	279/287	< –40
	T	520	687	29	76	323	417	33	268/279	< –40
60	L	472	652	30	72	-	-	-	266/279	< –40
	T	480	653	30	74	391	391	32	291/293	< –40
85	L	464	635	31	73	-	-	-	254/282	–29
	T	461	635	31	73	312	396	31	154/246	–29

Table 8 Properties of welded joint

Welding method	Welding material	Heat input	Tensile test					Charpy test	
		(kJ/mm)	Temperature	Test piece	YS(MPa)	TS(MPa)	El(%)	Notch position	$_vE_0$(J)
SMAW	L-62 4.0mmø	1.74-1.99	Room temp.	Joint	596	658	23	WM	173
			600°C	Joint	341	417	20	FL	211
				WM	312	398	33	HAZ	230
SAW	Y-DM 4.8mmø YF-15B	BP1:3.2 BP2-LP: 4.5	Room temp.	Joint	571	692	19	WM	82
			600°C	Joint	364	431	22	FL	101
				WM	367	436	29	HAZ	83
	Y-DL•FR 6.4mmø NB-52FRM	10.3-15.7	Room temp.	Joint	510	620	19	WM	39
			600°C	Joint	303	376	23	FL	53
				WM	309	341	35	HAZ	52
	Y-DL•FR 6.4mmø NSH60FRS	44.0	Room temp.	Joint	515	651	20	WM	53
			600°C	Joint	390	448	19	FL	42
				WM	376	404	16	HAZ	49
SESNET	Y-CM•FR 2.4mmø YF-15I	105.8	Room temp.	Joint	502	650	14	WM	171
			600°C	Joint	347	437	12	FL	39
				WM	399	471	17	HAZ	30

cipitation of complex carbonitride of Mo, Nb and V; and with the said fire-resistant steel, long-range resistance to dislocation motion remarkably increases in the temperature range up to 600°C.

Based on the above findings and thermodynamic equilibrium calculation, the optimized amount of Mo and microstructure required for robustly achieving the envisaged high-temperature properties of a new fire-resistant steel were technically and quantitatively determined, and thus a new 590 MPa class of fire-resistant steel for building structural use having both a 590 MPa class strength and high-temperature performance has been successfully developed. The developed steel fully satisfies the target properties at room and high temperatures as described above, and is applicable to fire-resistant structures without protective coating. Plates of the developed steel of 80 mm in thickness have been used for the see-through elevator frame (four-sided box structure) of the new Dentsu Head Office Building (owner: Dentsu, Inc., designer: Obayashi Corporation), one of the buildings of the Shiodome Area Redevelopment Project in Tokyo.

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