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Development and Practical Application of Fire-Resistant Steel for Buildings

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Abstract:

In steel-frame buildings, steel members should be protected by spraying fire-resistant materials so as not to be heated to higher than 350°C during fires. The work of spraying fire-resistant materials, however, has an injurious effect on the workers' health and is a time-consuming job. In addition, the usable space of the building is reduced by such fire-resistant coating. Therefore, there has been an increasing demand for restricting fire-resistant coatings. The development of fire-resistant steels for buildings was aimed at increasing steel's elevated-temperature strength while assuring earthquake resistance, weldability and other properties equal to or better than those of conventional steels for buildings. This paper first describes fundamental studies made of the effects of alloying elements and manufacturing conditions on elevated-temperature strength, and then presents the development of a fire-resistant steel which provides high strength at 600°C while ensuring good earthquake resistance and weldability.

1. Introduction

When a steel-frame building is exposed to a high-temperature during fires, its structural steel members lose their strength to such a degree that they no longer can maintain the proof stress (yield strength) required of building structurals. The Building Standards Act prescribes the protection of steel frames by fire-resistant coatings. This fire protection requirement mainly applies to buildings to be used by many, unspecified people, such as apartment houses and hotels, and buildings in urban areas. The main structural members of fire-resistant buildings, such as columns and beams, must be made as "fire-resistant construction." Since the current building law designates "fire-resistant construction" for each fire-resistance rating as shown in **Fig. 1**, the steel frames must be protected by such fire-resistant coatings that prevent the steel temperature from exceeding 350°C in the fire-resistance test.

At elevated temperatures of 350°C and above, the yield strength of steel drops to two-thirds or less of the specified room-temperature yield strength and falls below the structurally necessary yield strength (allowable stress for sustained loading). There was increasing demand for reducing the fire-resistant coating work from the viewpoints of reducing the construction cost, shortening the construction period, and effective utilization of interior space.

The Ministry of Construction's comprehensive technology development project "comprehensive fire-resistant design system for building fire safty" was completed in March 1987. The "new

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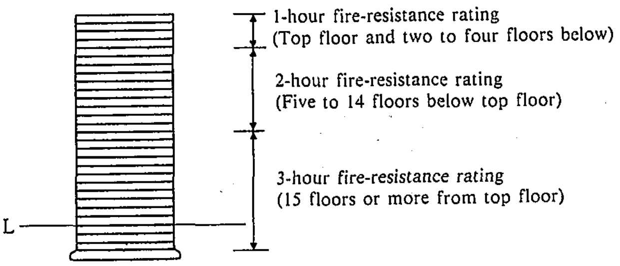


Fig. 1 Building floors and legal fire-resistance ratings

fire safty design system'' were brought into effect for evaluating the fire safety of buildings without the designation of fire-resistant construction[1]. Since the new fire safty design system allows the maximum permissible steel temperature to be set in terms of elevated-temperature yield strength of the steel, it has become possible to use new materials and design techniques in the field of fire-resistant design of steel structures. If a new steel with high elevated-temperature yield strength superior to that of conventional steels and fire-resistant steel-frame structures made of such steel are developed, the fire-resistant coating work will be sharply reduced.

Steels with excellent elevated-temperature strength, centering on heat-resistant steels, have been researched for such applications as medium- and high-temperature pressure vessels and boiler tubes. These steels are used at elevated temperatures for long periods and are different from fire-resistant steels that must withstand fires for shorter periods. High earthquake resistance (low yield ratio (YR)) and good weldability are also demanded of steels for buildings.

In response to such needs, Nippon Steel swiftly acted to start work on the development of steels with excellent fire resistance, and succeeded in developing a fire-resistant steel for building construction which guarantees high-temperature resistance at 600°C.

This paper describes the fundamental studies made of the effects of alloying elements, microstructures and manufacturing conditions on the elevated-temperature strength of steels, and presents the service performance properties and application examples of the new fire-resistant steel produced at the mill on the basis of the study results.

2. Target of Development

One of the most important subjects in the development of fire-resistant steel is setting the temperature at which the desired elevated-temperature strength can be guaranteed. Creusot-Loire, a steelmaker in Europe where fire protection is advanced, carried out research on a molybdenum steel capable of withstanding fire temperatures of 900 to 1,000°C,[2,3] but did not commercialized it. In Japan, buildings must have both earthquake resistance and fire protection. The main theme here is how to satisfy the specified elevated-temperature strength for a short time of 1 to 3 hrs. while ensuring earthquake resistance and weldability equal to or better than those of conventional steels for buildings. The fire resistance of buildings depends not only on the steel used, but also on the design system employed and the thickness of fire-resistant coating applied. It is thus of extreme importance to determine the optimum balance between the allowable fire-resistance temperature and the steel manufacturing cost.

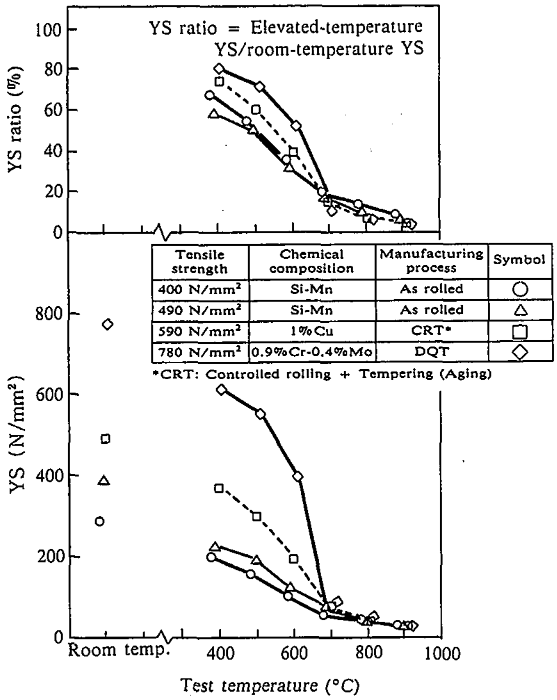


Fig. 2 Elevated-temperature tensile test results of conventional steels

An experimental study was performed to determine the temperature at which the desired elevated-temperature strength can be guaranteed. Four typical steels with tensile strengths of 400 to 780 N/mm^2 were put to elevated-temperature tensile tests. The results are given in **Fig. 2**. Round specimens with a diameter of 10 mm (gauge length : 40 mm) were machined from steel plates in the rolling direction, heated at the rate of 10°C/min to the test temperature, held at the temperature for 15 min., and tested in accordance with JIS G 0567. These conditions were applied to all elevated-temperature tensile tests reported here.

The test results of **Fig. 2** may be summarized as follows:

(1) For each steel tested, the yield strength steeply decreases as the temperature passes the 500°C-600°C range, and is as low as about 50 N/mm^2 at 700°C or higher.

(2) Direct quenching after rolling and tempering (DQT) increases the yield strength at elevated temperatures, but the loss of yield strength is large in the high-temperature region of 600°C and above. The loss of yield strength in the vicinity of 600°C is smaller in as-rolled (air cooled after rolling)steels.

If the strength guarantee temperature is to be set at 700°C according to these results, alloying elements must be added in large amounts, making it difficult to secure good weldability, nor to avoid a drastic increase in the manufacturing cost. A lower strength guarantee temperature of 500°C, on the other hand, allows only a slight saving of the fire-resistant coating, which betrays the purpose of using the fire-resistant steel from the beginning. Accordingly, the strength guarantee temperature of the fire-resistant steel was set at 600°C . The yield strength of the fire-resistant steel at 600°C was set at the minimum of two-thirds of the specified room-temperature yield strength by reference to the Building Standards Act. The development target of the fire-resistant steel are as shown in **Table 1**.

Table 1 Development target of fire-resistant steel for buildings

(1) Tensile properties Tensile strength: 400 to 490 N/mm² Elevated-temperature yield strength at 600°C: Equal to or greater than two-thirds of specified room-temperature yield strength Yield ratio at room temperature: 80% or less
(2) Weldability and other properties: Equal to or better than conventional steels

3. Fundamental Studies on Improvement of Elevated-Temperature Strength

A laboratory study was conducted to examine if the yield strength requirement at the elevated temperature of 600°C could be satisfied together with the other property requirements of building construction steels. Since the elevated-temperature yield strength is considered to depend largely on chemical composition and microstructure, the investigation was centered on the effects of these factors. As can be seen from **Fig. 2**, the elevated-temperature yield strength increases with increasing room-temperature yield strength. When the room-temperature yield strength is increased by quenching and tempering, however,the decline of yield strength at elevated temperatures becomes more drastic than for as-rolled steels. To obtain an excellent elevated-temperature yield strength while maintaining the desired room-temperature strength and yield ratio, it is essentially important to improve the ratio of yield strength at room temperature to that at 600°C (hereinafter called the yield strength ratio) in a steel mainly composed of ferrite (polygonal ferrite).

3.1 Effect of alloying elements on elevated-temperature strength

(1) Test methods

Twenty- and fifty-kilogram lots of steel were melted in a vacuum melting furnace in the laboratory and cast into 20-kg and 50-kg ingots. **Table 2** shows the chemical compositions of the steels melted. Steel A was based on the C-Mn-Cr-Nb system and was used to study the effect of molybdenum addition. Steel B was used to investigate the effects of single niobium or molybdenum addition and combined niobium-molybdenum addition. After reheating at 1,100°C each ingot was rolled to a 30-mm thick plate at a finish rolling temperature of 890 to 920°C. The tensile properties of the plates were tested using round specimens with a diameter of 10 mm (gauge length : 40 mm) machined from each plate in the rolling direction. The elevated-temperature test was conducted in accordance with JIS 0567. The microstructures of the plates were observed under an optical microscope, and the ferrite area fraction and ferrite grain size were measured.

(2) Effect of molybdenum addition on elevated-temperature yield strength

Fig. 3 shows the effect of molybdenum addition on the tensile properties and ferrite area fraction of the steel plates. Increasing the molybdenum content slightly reduces the room-temperature yield strength, linearly increases the elevated-temperature yield strength, and markedly improves the yield strength ratio. A 0.6% increase in the molybdenum content raises the yield strength ratio from 40 to 85%. The room-temperature yield ratio is lowered by the molybdenum addition. This decrease in the room-temperature yield ratio is considered to be caused mainly by a slight increase in the bainite area fraction in the microstructure.

According to these test results, molybdenum significantly improves the elevated-temperature yield strength of steel predominantly composed of ferrite, and a molybdenum addition

Table 2 Chemical compositions of laboratory-melted steels (wt %)

Steel	Base composition	Varied elements
A	0.14C-1Mn-0.5Cr-0.02Nb	Mo: 0-0.59
B	0.1C-0.9Mn	Nb: 0.018, Mo: 0.47

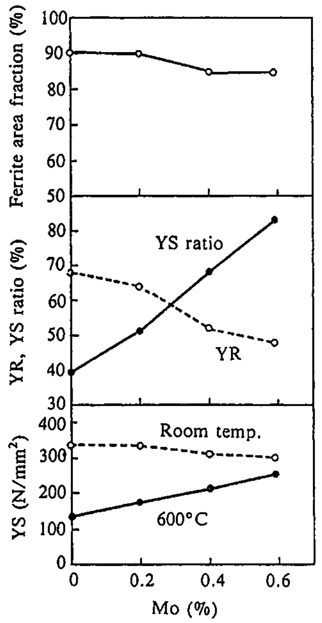


Fig. 3 Effect of molybdenum additions on tensile property and ferrite area fraction of steel plates

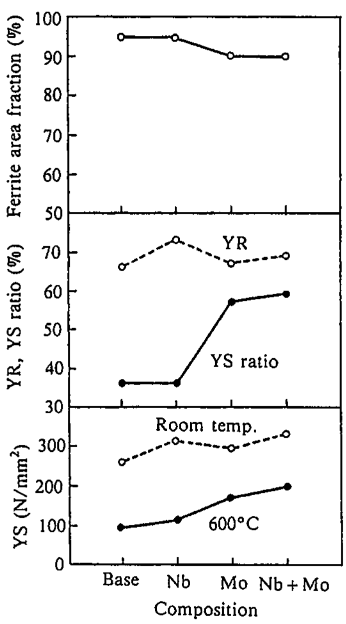


Fig. 4 Effects of single niobium and molybdenum additions and combined niobium-molybdenum addition on tensile property and ferrite area fraction of steel plates

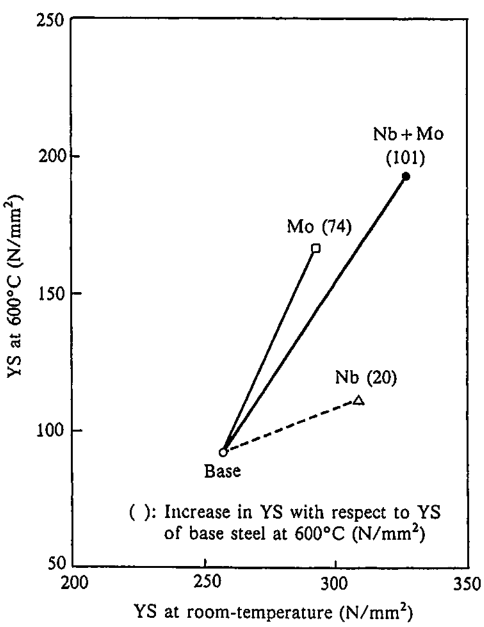


Fig. 5 Effects of single niobium and molybdenum additions and combined niobium-molybdenum addition on tensile property of steel plates

of about 0.5% is considered essential for fire-resistant steels with a tensile strength of 400 to 490 N/mm^2.

(3) Effects of single niobium and molybdenum additions and combined niobium-molybdenum addition on elevated-temperature yield strength

Figs. 4 and **5** show the effects of single niobium and molybdenum additions and combined niobium-molybdenum addition on the tensile properties and ferrite area fraction of the steel plates. Each steel has a microstructure predominantly composed of ferrite, and the ferrite area fraction is 90 to 95%. The addition of niobium to the base steel hardly changes the yield strength and increases the elevated-temperature yield strength by 20 N/mm^2. The niobium addition reduces the ferrite grain size and increases the room-temperature yield ratio by about 10%.

The single addition of molybdenum reduces the ferrite area fraction by about 5% and improves the elevated-temperature yield strength by a significant 74 N/mm^2. The room-temperature yield ratio does not differ from that of the base steel. The niobium-molybdenum microalloyed steel increases in the elevated-temperature yield strength by 101 N/mm^2, which is slightly larger than the sum of increases brought about by the single additions of niobium and molybdenum. The yield strength ratio and room-temperature yield strength are not appreciably different from those of the molybdenum steel. A small amount niobium addition improves strength at room and elevated temperatures without deteriorating weldability. The combined addition of niobium and molybdenum is thus considered as a powerful means for enhancing the tensile properties of fire-resistant steels for buildings.

(4) Effect of second phase on elevated-temperature strength

Fig. 6 shows the effect of the area fraction of the second phase (microstructure other than ferrite) on the strength and yield strength ratio of the steel plates. Irrespective of the chemical composition, the increase of second-phase area fraction (particularly that of bainite) increases the room-temperature and elevated-temperature yield strength and the yield strength ratio, but makes it more difficult to control the room-temperature tensile strength and yield ratio. Even with a low second-phase area fraction, single molybdenum addition and combined niobium-molybdenum addition significantly increase the elevated-temperature yield strength and yield strength ratio.

Fig. 7 shows the effect of the ferrite grain size on the yield strength and yield strength ratio of the steel plates shown in **Figs. 4** and **5**. The increase of ferrite grain size decreases the room-temperature yield strength, but increases the elevated-temperature yield strength and enhances the yield strength ratio. It is known that the grain coarsening of ferrite improves the elevated-temperature strength by suppressing grain-boundary slip at elevated temperatures.

(5) Mechanism of elevated-temperature strength improvement in niobium-molybdenum microalloyed steel[4)]

When the steel has a microstructure predominantly composed of ferrite, the combined addition of molybdenum and niobium is an effective method for enhancing strength without deteriorating weldability. The resultant chemical composition is considered ideal for fire-resistant steel for buildings. To clarify the mechanism whereby the elevated-temperature strength of the niobium-molybdenum microalloyed steel is improved, the morphology of the niobium and molybdenum in the niobium steel, molybdenum

	Composition
○	0.1%C-0.9%Mn
△	0.1%C-0.9%Mn-0.5%Mo
□	0.1%C-0.9%Mn-0.02%Nb
◇	0.1%C-0.9%Mn-0.5%Mo-0.02%Nb
●	0.14%C-1%Mn-0.5%Cr-0.02%Nb
▲	0.14%C-1%Mn-0.5%Cr-0.02%Nb-0.2%Mo
■	0.14%C-1%Mn-0.5%Cr-0.02%Nb-0.4%Mo
◆	0.14%C-1%Mn-0.5%Cr-0.02%Nb-0.6%Mo

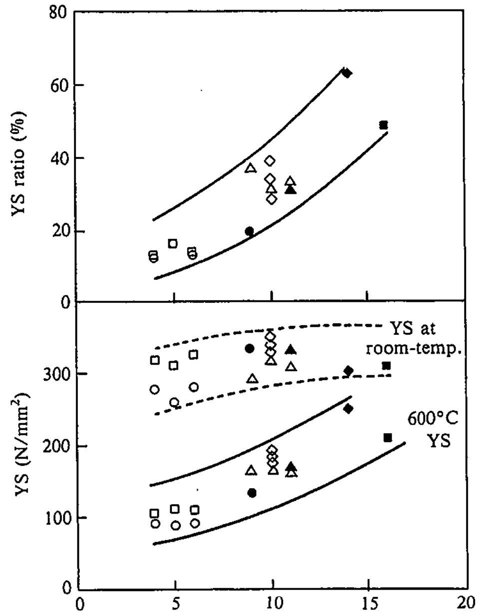


Fig. 6 Effect of second-phase area fraction on strength and YS ratio of steel plates

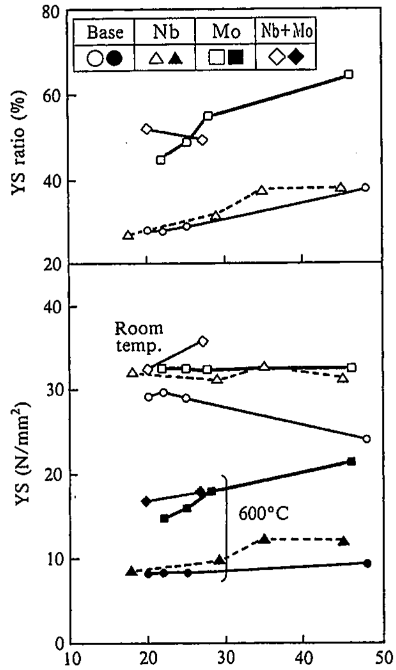


Fig. 7 Effect of ferrite grain size on yield strength and yield strength ratio of steel plates

Nb steel Mo steel Nb + Mo steel

Photo 1 FIM images of niobium steel, molybdenum steel, and niobium-molybdenum steel (precipitate size < 5 nm)

steel and niobium-molybdenum steel shown in **Figs. 4** and **5** were examined with an atom probe-field ion microscopy (AP-FIM)[4,5].

Photo 1 shows the FIM images of the niobium steel, molybdenum steel, and niobium-molybdenum steel. Nb(C, N) (≦ 5 nm) was observed in the niobium steel, acicular Mo_2C and molybdenum clusters were observed in the molybdenum steel, and NbC, Mo_2C and molybdenum clusters were observed in the niobium-molybdenum steel. Although molybdenum precipitates are recognized in both the molybdenum steel and niobium-molybdenum steel, most of the molybdenum added is shown to be in solid solution.

Fig. 8 shows the ladder diagrams obtained from AP analysis of niobium precipitates in the niobium-molybdenum steel to indicate another important role of molybdenum. The niobium precipitates in the niobium-molybdenum steel are not simple NbC, but include molybdenum segregation at the interface between NbC and ferrite matrix. This molybdenum segregation has the function of keeping NbC fine at elevated temperatures for a long period and is considered to improve the elevated-temperature yield strength. The results of the AP-FIM analysis may be summarized as follows:

Niobium steel:
  Strengthening of ferrite matrix by NbC (precipitation hardening)

Molybdenum steel:
  Strengthening by solid solution of molybdenum into ferrite (solid-solution hardening) and strengthening of ferrite matrix by precipitation of Mo_2C and molybdenum clusters (precipitation hardening)

Niobium-molybdenum steel:
  Besides the benefits of single niobium and molybdenum additions, inhibition of NbC growth (coarsening) by molybdenum segregation to NbC-matrix interface

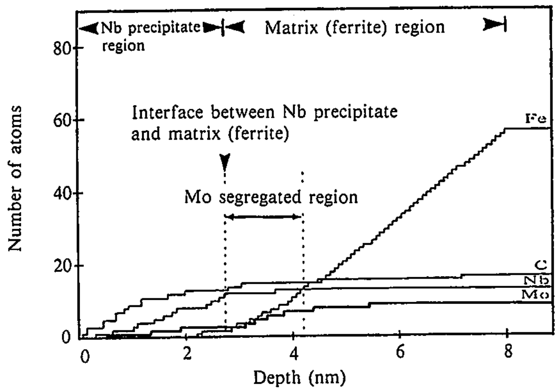


Fig. 8 Ladder diagrams obtained from AP analysis of niobium precipitates in niobium-molybdenum steel

3.2 Effect of manufacturing conditions on elevated-temperature strength

(1) Test methods

The plate manufacturing process and the effects of slab reheating temperature and finish rolling temperature in the as-rolled process were studied in the laboratory using continuously cast slabs produced at the mill. The chemical composition of the test steel is 0.1%C-0.3%Si-1.0%Mn-0.5%Cr-0.48%Mo-0.02%Nb-0.01%Ti. In the study of the plate manufacturing process, 32-mm thick plates were manufactured by the as-rolled process as well as by accelerated cooling and tempering, normalizing and tempering (NT), and quenching and tempering (QT) after rolling. In the study of slab reheating temperature in the as-rolled process, 25-mm plates were rolled at a finish rolling temperature of about 900°C by changing the slab reheating temperature. In the study of the finish rolling temperature, 25-mm plates were rolled by fixing the slab reheating temperature at 1,200°C and changing the finish rolling temperature.

The tensile properties and microstructures of the steel plates were investigated by the same methods as described in 3.1(1).

(2) Effect of plate manufacturing conditions on elevated-temperature yield strength

Fig. 9 shows the effect of plate manufacturing conditions on the tensile properties of steel plates. Accelerated cooling and QT treatment after rolling markedly increase the room-temperature yield strength and elevated-temperature yield strength by transformation strengthening (microstructural change to bainite or martensite). These treatments, however, decrease the yield strength ratio and increases the yield ratio. For steels with a tensile strength of 400 to 490 N/mm², the as-rolled process is considered most suited to the manufacture of fire-resistant steels for buildings. On the basis of the as-rolled process, the effects of the slab reheating temperature and finish rolling temperature on tensile properties and microstructure were investigated.

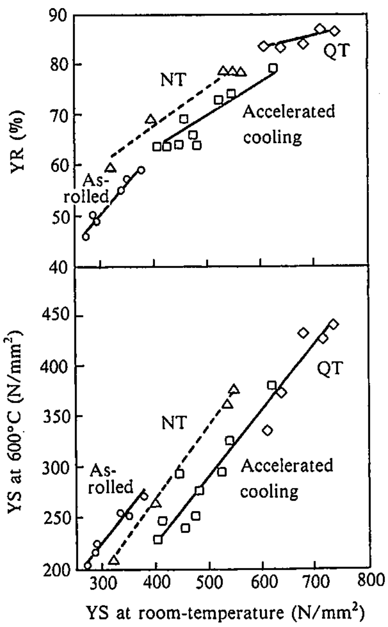


Fig. 9 Effect of plate manufacturing conditions on tensile property of plates

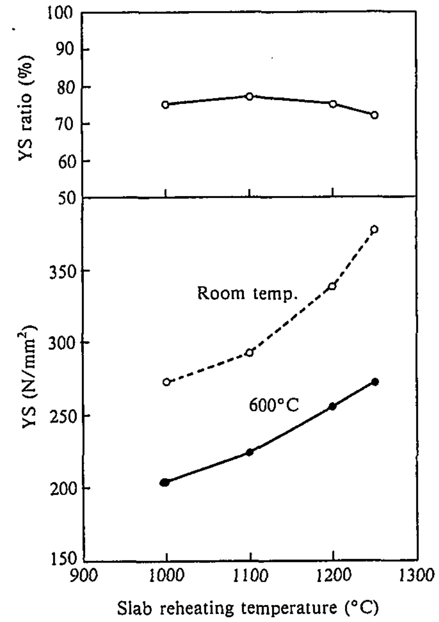


Fig. 10 Effect of slab reheating temperature on tensile property of steel plates

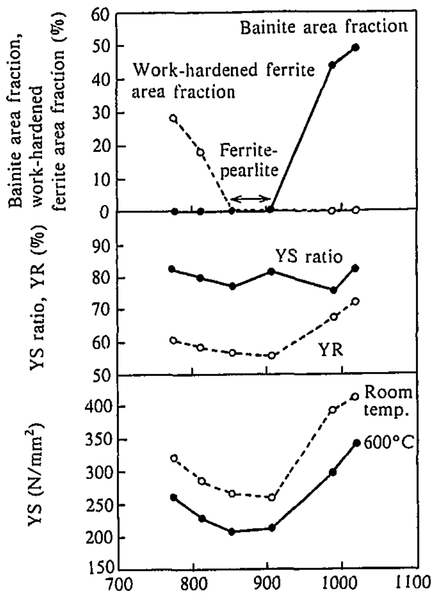


Fig. 11 Effect of finish rolling temperature on tensile property and microstructure of steel plates

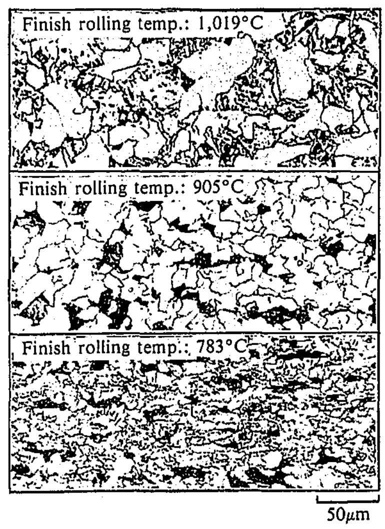


Photo 2 Effect of finish rolling temperature on microstructure of steel plates

(3) Effect of slab reheating temperature on elevated-temperature yield strength

Fig. 10 shows the effects of slab reheating temperature on the tensile properties of steel plates. As the slab reheating temperature rises, both the room-temperature and elevated-temperature yield strengths increase, and the yield strength ratio drops slightly. The increase of yield strength may be ascribed to the combined effect of the increase of niobium in solid solution, that of bainite fraction and the coarsening of ferrite grain size. Slabs must be reheated at high enough temperatures from the standpoint of the effective utilization of niobium.

(4) Effect of finish rolling temperature on elevated-temperature yield strength

Fig. 11 shows the effect of the finish rolling temperature on the tensile properties and microstructure of steel plates. As the finish rolling temperature falls, the room-temperature yield strength and elevated-temperature yield strength decrease, reach the minimum values in the vicinity of 900°C, and then increase. When the finish rolling temperature is near 1,000°C, the microstructure coarsens, and the bainite area fraction increases. When the finish rolling temperature is 800°C or lower, rolling in the ferrite-austenite two-phase region work hardens the ferrite, which in turn raises the yield strength. The room-temperature yield ratio exhibits almost the same tendency as the yield strength. The yield strength ratio changes little with the finish rolling temperature.

Photo 2 shows the change in the plate microstructure with the finish rolling temperature. The microstructure is ferrite-pearlite at finish rolling temperatures of 800 to 950°C, ferrite-pearlite containing work hardened ferrite at lower finish rolling temperatures, and coarse ferrite and bainite at higher finish rolling temperatures. In this way, the microstructure widely changes with the finish rolling temperature to change the mechanical properties of the steel plate. An optimum rolling temperature must be selected taking into account all the desired properties, including tensile and toughness, of the steel plate.

4. Properties of Fire-Resistant Steel Trially Produced at Mill

On the basis of the results of basic laboratory studies, a fire-resistant steel with a tensile strength of 490 N/mm^2 was trially produced at the mill and its service performance was examined.

4.1 Chemical composition and manufacturing process

Chromium-bearing niobium-molybdenum steel was melted in a 300-ton basic oxygen furnace and continuously cast into 240-mm thick slabs. After reheating to 1,100 to 1,150°C, the slabs were rolled to 25, 32 and 50-mm-thick plates at finish rolling temperatures of 900 to 930°C.

4.2 Basic properties of base metal

Table 3 shows the mechanical properties of the base metal. The room-temperature strength fully meets the specified value of SM490A, and the yield ratio, a measure of earthquake resistance, is as low as less than 80%. The Charpy impact absorbed energy at 0°C is good at greater than 100 J. The subsequent evaluation tests were conducted on 32-mm-thick steel plates.

Table 3 Mechanical properties of trial steel

Plate thickness (mm)	Direction of test*1	Tensile property (full-thickness JIS No. 1 specimen)				Charpy impact energy
		YS (N/mm^2)	TS (N/mm^2)	El*2 (%)	YR (%)	$_vE_0$ (J)
25	L	384	587	26	65	250
	T	368	588	22	62	168
32	L	349	569	22	61	294
	T	354	570	25	62	246
50	L	416	599	22	69	131
	T	383	584	24	66	107

*1 L: Longitudinal direction, T: Transverse direction
*2 El: Elongation

Fig. 12 shows the temperature dependence of strength. The fire-resistant steel has a smaller decrease of strength at elevated temperatures than the conventional steel SM490A, retaining more than two-thirds of the room-temperature yield strength even at 600°C.

Fig. 13 compares the fire-resistant steel and conventional steel SM490A in the temperature dependence of Young's modulus. The Young's modulus of the conventional steel steeply drops at 600°C, but that of the fire-resistant steel is as high as about 75% even at 600°C, and is kept still high up to about 700°C.

Fig. 14 compares the creep properties of the fire-resistant steel and the conventional steel SM490A. The conventional steel produces a large creep strain in short periods even at a small applied stress of 98 N/mm^2, while the creep strain of the fire-resistant steel is small at the applied stress of 196 N/mm^2.

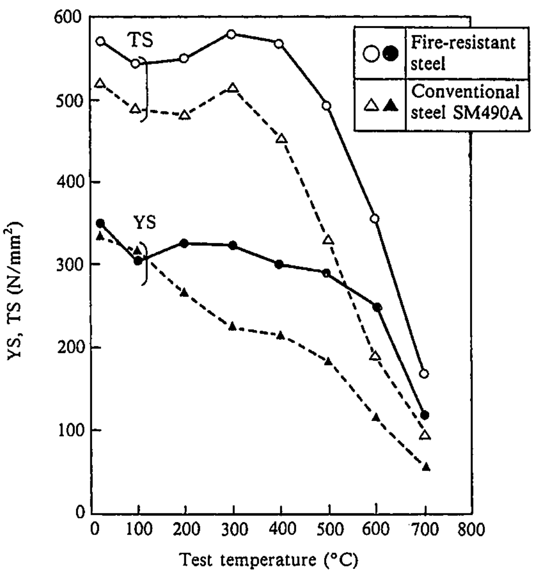


Fig. 12 Temperature dependence of strength

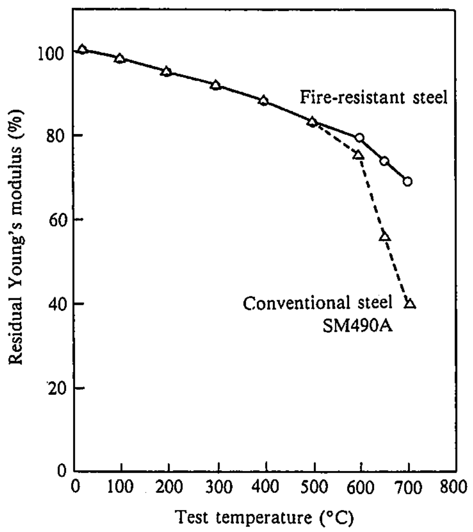


Fig. 13 Temperature dependence of Young's modulus

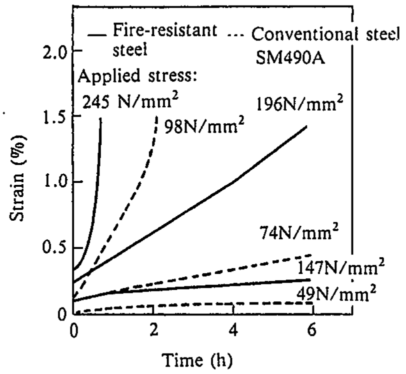


Fig. 14 Creep property comparison of fire-resistant steel and conventional steel SM490A (test temperature: 600°C)

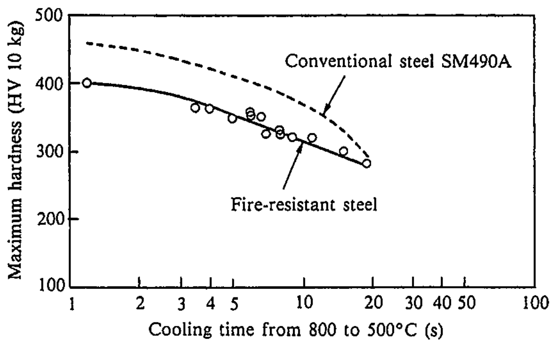


Fig. 15 Taper hardness test results

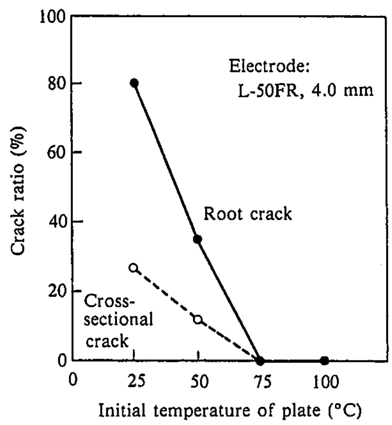


Fig. 16 Y-groove weld cracking test results

4.3 Weldability and welded joint performance

Fig. 15 shows the taper hardness test results of the fire-resistant steel and the conventional steel SM490A, while **Fig. 16** gives the Y-groove weld cracking test results of the fire-resistant steel. The hardness of the heat-affected zone (HAZ) and the preheating temperature required to prevent weld cracking are lower for the fire-resistant steel than the conventional steel. The good weldability of the fire-resistant steel may be explained as follows. Despite the addition of such alloying elements as niobium and molybdenum, the carbon and manganese contents are reduced to keep the P_{CM}, an index of weldability, at a low level.

Table 4 shows the properties of various welded joints used

Table 4 Properties of various welded joints

Welding process	Welding material*1	Tensile strength						Bend (JIS Z 3124)		Charpy impact energy	
		Test temperature	Specimen	YS (N/mm^2)	TS (N/mm^2)	El (%)	Fracture location	Bending direction (r = 1.5t)	Judgment	Notch location	$_vE_0$ (J)
SMAW Double-V groove 35 kJ/cm	Welding rod N-OS	Room temperature	Joint No. 1	—	615	36	Base metal	Surface bend	Good	WM	96
		600°C	Weld metal	340	396	28	—			FL	195
			Joint	266	359	35	—	Root bend	Good	HAZ	196
SAW Double-V groove 45 kJ/cm	Wire Y-C Flux YF-15K	Room temperature	Joint No. 1	—	619	35	Weld metal	Surface bend	Good	WM	102
		600°C	Weld metal	279	337	37	—			FL	130
			Joint	275	349	20	—	Root bend	Good	HAZ	146
	Wire Y-DM Flux NF-16	Room temperature	Joint No. 1		631	32	Base metal	Surface bend	Good	WM	99
		600°C	Weld metal	356	422	32	—			FL	144
			Joint	291	357	21	—	Root bend	Good	HAZ	112
SES Single-square groove 709 kJ/cm	Y-DM SES-15	Room temperature	Joint No.1	—	638	11	Base metal	Surface bend	Good	WM	61
		600°C	Weld metal	353	431	30	—			FL	29
			Joint	362	438	24	—	Root bend	Good	HAZ	34

*1 Nippon Steel Welding Products & Engineering Co., Ltd.

on building structures. Various welded joints were made by low-heat input shielded metal-arc welding (SMAW), medium-heat input submerged-arc welding (SAW), and extrahigh-heat input simplified electroslag welding (SES), and their mechanical properties were examined. Since the weld metal of the fire-resistant steel must be provided with high elevated-temperature strength, appropriate welding consumables were selected for the fire-resistant steel, taking into consideration the room-temperature and elevated-temperature strength of the weld metal. All welded joints of the fire-resistant steel have sufficient strength and good bend properties at room temperature and 600°C. The Charpy impact absorbed energy in the weld metal (WM), heat-affected zone (HAZ), and fusion line (FL) are high enough in SAW joints made with a heat input of 45 kJ/cm. The SES welded joints made with an extrahigh heat input of 790 kJ/cm are rather low in the impact energy, but are still comparable to the conventional steel SM490A.

The fire-resistant steel for building construction featuring excellent properties as described above is available in H-shapes, sheets and pipes as well as plates. High-strength bolts and various welding materials are already available for use with the fire-resistant steel.

Fire-resistant steels have far higher allowable temperatures than conventional steels. The application of fire-resistant steels to buildings makes it necessary to fully study the performance of columns and beams and the deformation behavior of frames at elevated temperatures, and to develop fire-resistance design techniques capable of guaranteeing safely in fires. Nippon Steel has developed programs for analyzing fire-resistant steel frames and techniques for verifying the fire-resistant performance of full-size structural components and applying the results to actual design of fire-resistant buildings[6-12].

5. Commercial Application of Fire-Resistant Steels in Buildings

Through the application of the new fire-resistance design system, fire-resistant coating can be drastically reduced, and bare steel frame structures can be constructed if the building under consideration is individually approved as to their fire-resistant performance. Buildings actually constructed using fire-resistant steels are introduced below.

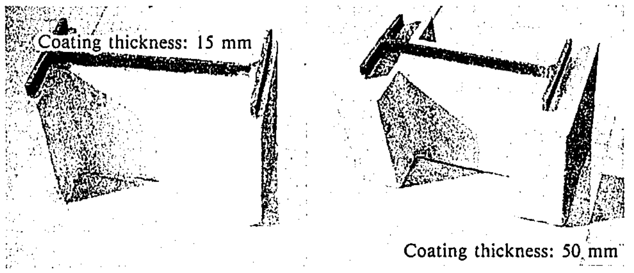
5.1 Building with drastically reduced fire-resistant coating thickness (Second Nippon Steel Building)

The Second Nippon Steel Building (consisting of building A of 15 stories above ground and building B of 10 stories above ground) was the first building constructed using fire-resistant steel. The columns and beams are all made of fire-resistant steel. About 3,000 tons of fire-resistant steel was used in the building. A new fire-resistant steel frame structure system was adopted to achieve a drastic reduction in fire-resistant coatings (dry and wet rock wool coatings).

Photo 3 shows the reduction in the fire-resistant coatings. The fire-resistant coating thickness of the fire-resistant steel is one half to one third of that of the conventional steel. For example, a column with a 3-hour fire-resistance rating must be usually covered with 50 mm of rock wool. The use of the fire-resistant steel steeply reduces the covering thickness to 15 mm.

5.2 Building with bare fire-resistant steel construction (Tobihata Building)

The Tobihata Building is a bare steel-frame building realized



Fire-resistant steel Conventional steel

Photo 3 Effect of fire-resistant steel in reducing fire-resistant coating thickness

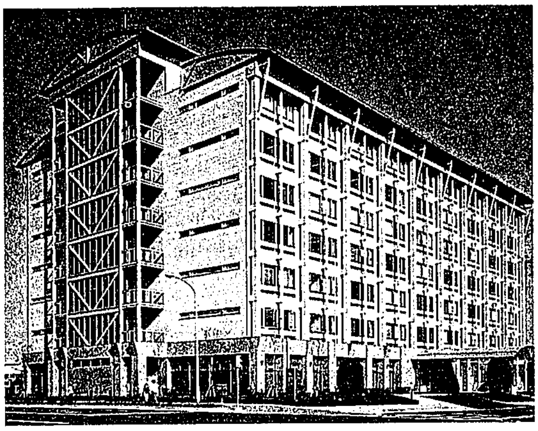


Photo 4 General view of Tobihata Building

by arranging fire-resistant steel columns and beams outside. A general view of this building is shown in **Photo 4**. To leave the outside steel frames bare, it must be confirmed that the steel frame temperature does not exceed 600°C in fires. Calculations of the shape and temperature of flames emitting out of windows and of the steel temperature proved that the steel temperature would be 543°C at most and would never reach 600°C.

Fire-resistant steels are used in many other buildings, such as office buildings, commercial buildings, hotels, multistory garages, and gymnasiums[13].

6. Conclusions

(1) The appropriate guarantee temperature for the elevated-temperature strength of fire-resistant steels for buildings is 600°C when weldability and manufacturing cost are taken into account.

(2) The elevated-temperature strength of fire-resistant steels is affected by alloying elements and microstructure. Considering the room-temperature yield ratio and yield strength ratio, a microstructure predominantly composed of ferrite is suited to fire-resistant steels with a tensile strength of 400 to 490 N/mm^2. The as-rolled condition is best suited for such fire-resistant steels.

(3) Molybdenum and chromium are effective in improving the elevated-temperature strength of predominantly ferritic steels. The addition of niobium and molybdenum combined is particularly effective for the purpose.

(4) A trially mill-produced niobium-molybdenum microalloyed fire-resistant steel of 490 N/mm^2 tensile strength exhibited excellent base-metal properties, weldability, and welded joint performance. The development of the fire-resistant steel, coupled with a progress made in the fire-resistant design technique, has significantly reduced the use of fire-resistant coatings of building steel frames, and even has made bare steel-frame structures a reality.

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