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High Strength and Heavy Wall Thickness Steel Pipes for Building Structures†

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Abstract:

In recent years higher tensile strength and heavier section of steel pipes have been required for building structures. JFE Steel has developed a series of steel pipes from 550 to 780 N/mm^2 tensile strength class (from 385 to 630 N/mm^2 yield strength class) by applying high performance steel plates. Mechanical properties of the pipes, particularly yield strength (YS) and yield ratio (YR), are focused in order to achieve high performance for the building frames. Both low YR and high YR (high YS) types of pipes, which are required according to various design requests, can be produced through controlling the mechanical properties of applied plates and the manufacturing processes of the pipes.

1. Introduction

The main application of round steel pipes for building construction is column materials. In particular, concrete filled tubes (CFT) have frequently been widely used in recent years. The structural superiority of round CFTs in comparison with square steel pipes is widely recognized, and includes features such the confining effect in concrete filling and a sectional profile which is free of directionality. With regard to the building scale, the fact that round pipes are frequently used in comparatively large-scale structures in the mid- to high-rise range is a distinctive feature of this type (**Photo 1**). The most widely used sectional sizes, according the records of projects using round steel pipes cited by JFE Steel from 2000 to 2006 (**Fig. 1**), are outer diameters in the range of ϕ 600–800 mm and wall thicknesses of 20–40 mm. As manufacturing methods, the UOE method is widely adopted. Recently, however, unprecedented large section pipes with outer diameters of around ϕ 2 000 mm and wall thicknesses of >40 mm to 100 mm have been adopted in designs at a rate of several projects per year. JFE Steel has developed a series of high strength, heavy section round steel pipes from tensile strength (TS) class 490 N/mm^2 to 780 N/mm^2 (yield strength (YS) class 385 N/mm^2 to 630 N/mm^2) which suitable for these special projects, and has confirmed that these products satisfy the performance requirements of building construction applications. This paper presents the results of

Photo 1 Example of building using circular columns

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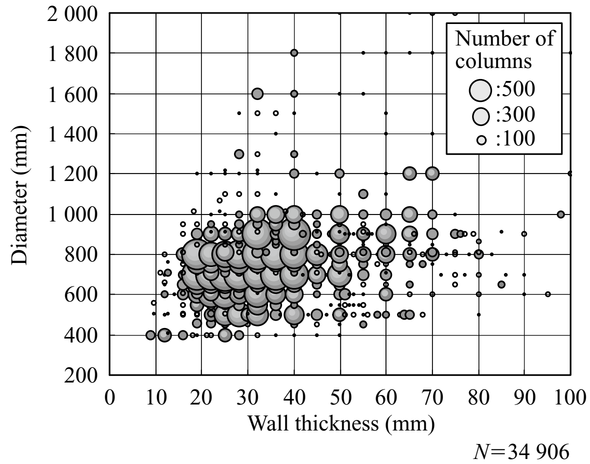


Fig. 1 Distribution of column size

trial manufacture for confirmation of the performance of these pipes.

2. Performance Requirements for Steel Pipes for Building Structures

2.1 Mechanical Properties

The current building design concept in Japan incorporates the concept of elasto-plasticity. Under this concept, it is thought that building collapse can be prevented by plasticization of the structural members and the resultant absorption of energy during a major earthquake, as assumed in the design. The concept of elasto-plastic design utilizes the performance of steel materials, which have a high plastic deformation capacity. Because it is possible to reduce the necessary cross section in comparison with elastic design, elasto-plastic design offers superior economy. Therefore, in the main members used in building structures, not limited to round steel pipes, standard values have been set with an awareness of allowing plasticization by setting the upper limit of yield strength (YS) and specifying the ratio (yield ratio YR = YS/TS) of yield strength (YS) and tensile strength (TS). The same concept has been incorporated in the STKN standard in Japanese Industrial Standards (JIS), which is the general standard for steel pipes used in column material applications. In the STKN standard, both the YS range and the TS range are specified as 105 N/mm^2, and YR is specified as 85% or less (welded steel pipes). For high strength steels which are not designated in the Building Standard Law of Japan, the approval of the Minister of Land, Infrastructure and Transport (MLIT) is necessary. However, in many cases, the specified values for steel pipes also follow the STKN standard in this case.

On the other hand, in recent years, there have been moves to change design practice from the specification code design used up to the present to performance code design. Thus, from the legal viewpoint, while setting certain limits, design with a comparatively high degree of freedom, suited to the performance requirements of individual buildings, has become possible for designers. As part of this trend, moves to adopt not only the conventional elasto-plastic design, but also elastic design, have also begun. As merits of adopting elastic design, in contrast to elasto-plastic design, in which it is necessary to consider the behavior of members as far as their plastic properties after complex yielding, the elastic design method is structurally clear, and above all, continuing use of all or part of buildings designed by the elastic method without damage is possible, even after an earthquake or other disaster. Because it is sufficient if adequate yield strength can be secured in the main members used in buildings of this type, use of high YR materials has become possible.

As outlined above, in steel materials for building structures, low YR steel pipes are required in elasto-plastic design, and high YR steel pipes (high YS pipes) are used in elastic design. JFE Steel has developed high strength, heavy section steel pipes which respond to these respective requirements. In particular, in high YR pipes, the company has held tensile strength to the level of the conventional steel grades and set YS at a high level in consideration of economy.

Where toughness is concerned, there has been heightened interest in this type of performance in the construction field due to the earthquake disasters of recent years. With steel pipes, there is a tendency to reduce the toughness value in comparison with the steel plate before processing because pipes are subject to plastic working in the manufacturing process. However, it is desirable to secure a toughness value on the same level as general steel plates after pipemaking.

2.2 Weldability

Welding of high strength steels generally involves a high degree of difficulty, including a high preheating temperature and strict control of the inter-pass temperature. Therefore, steel materials which enable sound welding with a low preheating temperature have been desired. The development reported here responded to that need by adopting steel plates which holds weld crack sensitivity composition (P_{CM}) to a low value.

2.3 Dimensional Accuracy

In steel building frames, JASS6 (Japanese Architectural Standard Specification – Steel Work[1)]) is generally used as the standard for dimensional accuracy. As a standard for round steel pipes for use in building structures, the JIS STKN standard is generally adopted. However, in this standard, precision of diameter is specified in terms of the diameter as converted from the circumfer-

Table 1 Targets for mechanical properties and chemical compositions of steel pipes

Steel pipe		Mechanical properties				Chemical composition
		YS (N/mm²)	TS (N/mm²)	YR=YS/TS	$_vE_0$*1 (J)	P_{cm}*2 (%)
TS490-550	P-385B	385–535	550–700	≤85% (Low YR)	≥70	≤0.27
	P-400T	400–600	490–640	≤95% (High YR)	≥70	≤0.27
TS570-590	P-440B	440–590	590–740	≤85% (Low YR)	≥47	≤0.30
	P-500T	500–700	570–740	≤95% (High YR)	≥70	≤0.30
TS780	P-630T	630–880	780–930	≤95% (High YR)	≥47	≤0.30

*1 1/4t trom surface
*2 P_{cm}: C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

ence of the tube, and both the measurement method and tolerances are different from those for circularity in JASS6, in which the provisions consider the linear misalignment which occurs in welds at pipe joints.

This difference becomes particularly large in large-diameter pipes. For example, in JIS, the tolerance for ϕ 2 000 mm is ±10 mm by conversion of the outer diameter from the circumference, but in contrast, in JASS6, the tolerance is ±3 mm specified as circularity. Thus, in building frames, consideration of JASS6, which requires relatively strict accuracy control, is demanded.

2.4 Development Targets

The object of this development was round steel pipes for column material applications in high rise buildings or structures. The target strength levels were divided into three classes, TS490 to 550 N/mm² class (YS385, 400 N/mm²), TS570 to 590 N/mm² class (YS440, 500 N/mm²), and TS780 N/mm² class (YS630 N/mm²), and low YR and high YR specifications were set for the respective strength levels. However, in the TS780 N/mm² class, the object of development was limited to high YR steel pipe. The toughness value and value of P_{CM} were set to values which secure a steel plate specification of the same strength class as that adopted in the building frame. The respective development target specifications are shown in **Table 1**.

3. Development Tasks and Concepts

3.1 Control of Mechanical Properties of Steel Plates

3.1.1 Yield ratio (YR)

As shown in **Fig. 2**, the YR of heavy steel plates generally increases with strength in steels. The average YR of the conventional TS570 to 610 N/mm² class steel plates exceeds 80%, and that of 780 N/mm² class plates exceeds 85%. In the steel plates with the high YR specification shown in Table 1, there are cases in which the conventional high YR plates can be applied without modification, but as steel pipe material for the low YR specification, it is necessary to apply low YR

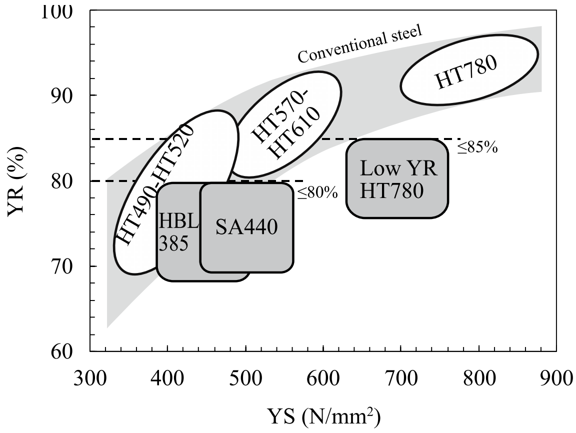


Fig. 2 Relationship between yield strength (YS) and yield ratio (YR) of steel plates

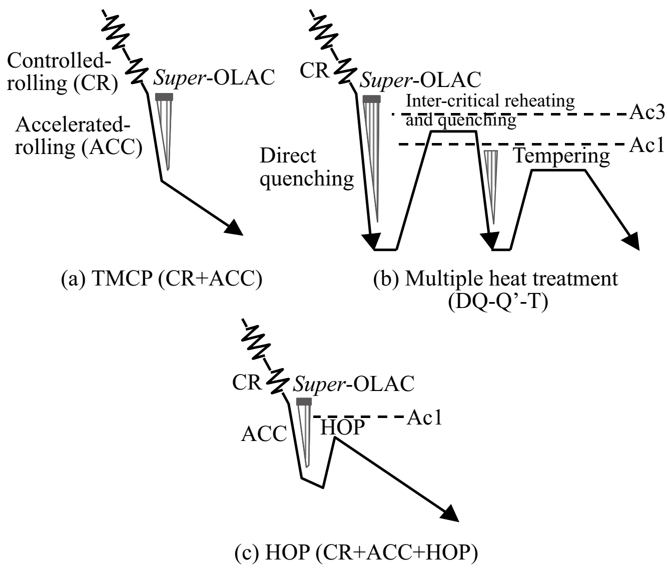
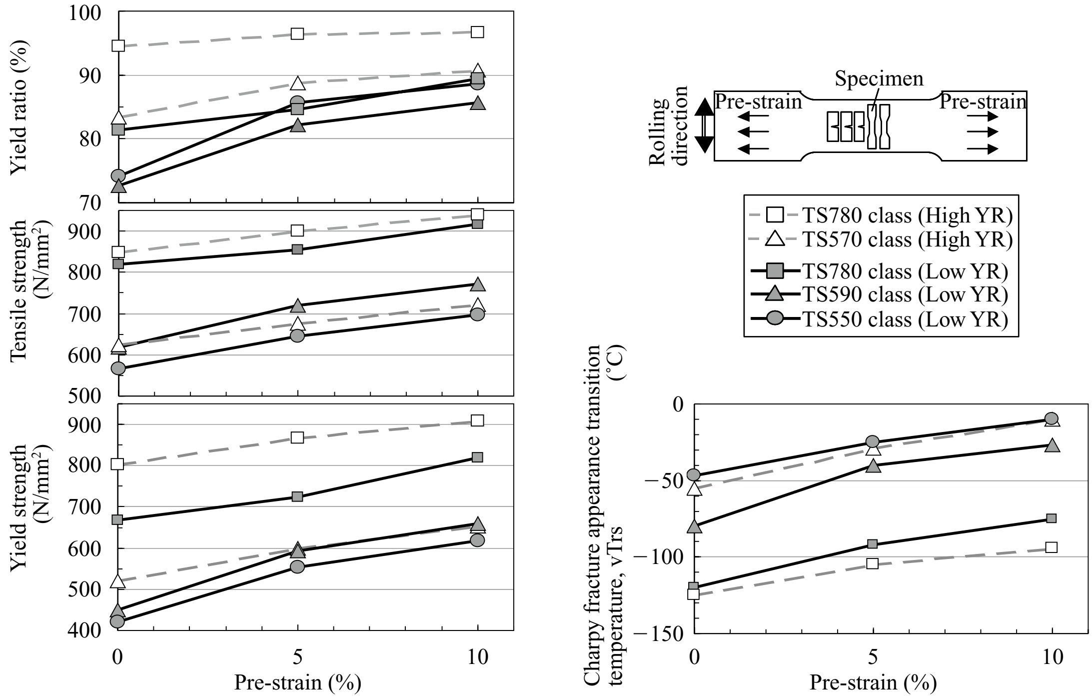


Fig. 3 Manufacturing processes for low yield ratio (YR) steel plates

plates with a YR controlled through the chemical composition and manufacturing process. **Figure 3** shows a schematic diagram of the manufacturing process for achieving low YR using JFE Steel's *Super*-OLAC (On-line Accelerated Cooling) technology. At the strength levels of 550 N/mm² class steel (HBL385[2)]) and below, low YR of 80% or less can be achieved by optimizing the thermo-mechanical control process (TMCP) as



(a) Tensile properties

(b) Charpy impact property

Fig. 4 Effects of strain aging on tensile and Charpy impact properties of steel plates

shown in Fig. 3(a). In higher strength steels, low YR of 80% or less can be achieved with 590 N/mm^2 class steel (SA440), and 85% or less can be achieved 780 N/mm^2 class steel (low YR-HT780; JFE-HITEN780T) by applying a complex multi-stage heat treatment process that includes inter-critical reheated quenching (Q'), as shown in Fig. 3(b). JFE Steel has obtained certification from the Minister of Land, Infrastructure and Transport for its low YR steel lineup with tensile strengths in the range from 490 to 780 N/mm^2.*

Recently, JFE Steel established an on-line heat treatment technology that realizes fine dispersed microstructural control of the hard martensite phase, which could only be achieved with the off-line Q' heat treatment process in the past, by applying the HOP® (Heat-treatment On-line Process)[3] using an on-line induction heating device which was introduced by JFE Steel for the first time in the world. As a result, JFE developed a low YR-HT780 steel by a non-heat treated process with HOP[4].

3.1.2 Change of mechanical properties due to bending forming

Bending forming in the pipemaking process introduces tensile or compressive plastic strain at the front and back sides of the pipe. At maximum, this strain is on the order of the ratio (t/D) of the plate thickness t and pipe diameter D. This causes changes in mechanical properties, including work hardening, embrittlement, etc. Thus, it is necessary to set the target properties of the steel plates which are to be applied as material for steel pipes considering the changes in mechanical properties before and after pipemaking.

Figure 4 shows the results of an evaluation of mechanical properties after aging heat treatment at 250°C × 1 h when 5% or 10% tensile prestrain was applied in the cold condition to prestrained test samples (parallel part: 18 t × 80 w × 180 L) taken in the plate transverse direction (C direction) from various types of steel plates (thickness: 40–60 mm) in the TS550 to 780 N/mm^2 classes. In order to simulate a tensile test of the pipe axial direction, round bar tensile test pieces and Charpy impact test pieces were taken in the rolling direction, which was perpendicular to the prestrain direction. Because the amount of plastic strain introduced by bending forming will differ depending on the plate thickness position, this type of simple tensile prestrain test does not faithfully reproduce forming in actual pipemaking. However, it can be used to obtain systematic basic data on the changes in mechanical properties due to plastic working.

According to the tensile test results shown in Fig. 4(a), YS, TS, and YR increase accompanying increases in prestrain, but the increment of YR is larger in low YR steel plates than in high YR plates. Thus, in

*TMCP steel materials for building structures (HBL325, HBL355, HBL385; Numerical values indicate yield point or proof stress), High performance 590 N/mm^2 steel material (SA440; YS440 N/mm^2 class), Low YR-HT780 steel (JFE-HITEN780T; YS630 N/mm^2 class).

Table 2 Results of y-groove weld cracking tests

Steel plate			Welding conditions	Preheating temperature (°C)	Crack ratio
Grade	P_{CM}	Thickness (mm)			
780 N/mm^2 class	0.27	60	GMAW (CO_2) Welding consumable: MG-80, ϕ 1.2 Heat input: 1.1 kJ/mm	75°C	0%
				50°C	0%
	0.24	40		50°C	0%
				25°C	0%
590 N/mm^2 class (SA440-U)	0.21	80	GMAW (CO_2) Welding consumable: MG-60(YGW-21), ϕ 1.2 Heat input: 1.1 kJ/mm	25°C	0%
				0°C	0%
550 N/mm^2 class (HBL385)	0.17	100		50°C	0%
				25°C	0%

Atmosphere: 20°C, 60%

order to satisfy the low YR specification for steel pipes, the target YR of the plate used as the base material is decreased further, or a process which reduces work hardening is applied, such as warm bending forming or heat treatment after pipemaking, as described in Section 3.2.

Figure 4(b) shows the effect of the amount of pre-strain on the Charpy fracture transition temperature (vTrs). All of the steel plates showed embrittlement as a result of strain aging, and vTrs increased by 30–50°C. Thus, with heavy steel plates which are to be applied as material for pipemaking, it is necessary to optimize the composition design and manufacturing conditions considering the reduction of toughness caused by bending forming.

3.1.3 Weldability (Lowering P_{CM})

JFE Steel has developed high strength, high performance steel plates which secure excellent weldability by reducing the carbon equivalent C_{eq} and weld crack sensitivity composition P_{CM} using high accuracy TMCP, taking advantage of its advanced accelerated cooling device, the *Super*-OLAC. As an example, **Table 2** shows the results of y-groove weld crack tests of the main low YR steel plates for building construction (550 N/mm^2 class steel (HBL385), high weldability type 590 N/mm^2 steel (SA440-U)[5]), and low YR-780 N/mm^2 class steel). With steel with under 590 N/mm^2 low, the preheating temperature for preventing cracking in CO_2 gas shield arc welding was room temperature or lower, showing that these steels possess weldability of a level at which preheating is generally unnecessary.

3.2 Pipemaking

3.2.1 Bending forming

Among the steel pipes for building structures produced by JFE Steel, with high strength, heavy wall thickness products such as those which were the object of this development, pipemaking is performed by the press bend method (**Photo 2**). In the press bend method, the steel plate material is subjected to 3-point bending at equal intervals with a press machine, and the required curvature is then obtained using a straightener. The restriction on this method is the capacity of the press. High press power is necessary in plastic bending forming through the full thickness of heavy gauge steel plates. In cases which exceed the capacity of the press machine, it is necessary to perform warm forming by heating the material before forming in order to reduce its deformation resistance. In this method, deformation resistance is reduced as the heating temperature increases, but work hardening also changes. Therefore, it is necessary to determine the press bend conditions considering changes in mechanical properties.

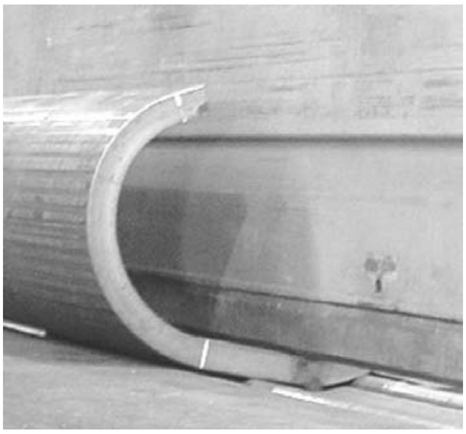


Photo 2 Press bending process

Furthermore, in order to secure dimensional accuracy after pipemaking, control of the dimensional accuracy of the material plate, a grasp of the press capacity, and an understanding of the amount of deformation caused by seam welding, become issues. Particularly in heavy-walled pipes, due to the large amount of welding and wide width of the seam bead, welding conditions such as groove size and welding heat input during welding are controlled from the viewpoint of securing dimensional accuracy.

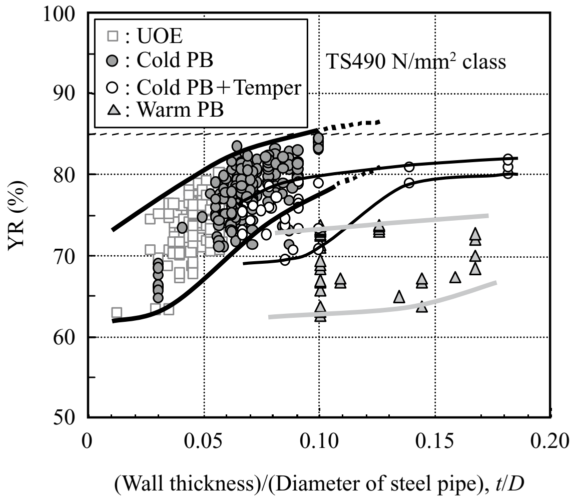


Fig. 5 Effects of warm bending and tempering on yield ratio (YR) of 490 N/mm^2 class pipes

3.2.2 Heat treatment

In steel pipes with cross sections having a large t/D value, work hardening due to the effect of plastic strain during cold bending forming may be excessive. In such cases, Excessive increases in YS, TS, and YR and reduction in toughness are alleviated by heat treatment during or after benging forming, such as warm bending or tempering so as to control the mechanical properties to within the required target range. **Figure 5** shows the reduction of YR by warm bending or tempering for 490 N/mm^2 class pipe as an example. Because the changes in mechanical properties due to warm bending or heat treatment after bending forming will differ depending on the chemical composition and microstructure of the base steel plate and t/D, the forming temperature and heat treatment conditions are determined for each composition, strength level, plate manufacturing method, and size.

4. Results of Pipe Manufacturing

4.1 Types of Pipes Manufactured and Results of Mechanical Tests

Steel pipes were manufactured in a wide range of sizes, including outer diameters of 800 to 2 100 mm, wall thicknesses of 40 to 100 mm, and t/D values from 4.2 to 7.8% in the strength range from tensile strength (TS) 490 N/mm^2 to 780 N/mm^2. Typical chemical compositions of these products are shown in **Table 3**, and the pipe sizes, corresponding pipemaking conditions, and mechanical properties are shown in **Table 4**. For mechanical properties, the data are shown for both the steel plates and the product pipes. As tensile test pieces, full thickness specimens were used. For pipes, samples were taken from the pipe axial direction, and for plates, from the same direction before pipemaking. As an impact test, the Chapry impact test was performed. The test piece sampling position for pipes was the pipe axial direction at the 1/4 thickness position from the outer surface of the pipe; for plates, the same position and direction before pipemaking were used.

4.2 Discussion

Table 3 shows that the values of P_{CM} of the sampled plates were capable of satisfying the target specifications. In particular, with steel pipes with TS490 to 550 N/mm^2 and TS570 to 590 N/mm^2, the values are substantially lower than the target specifications, demonstrating that a low P_{CM} composition which enables welding without preheating can be achieved by applying TMCP technology.

In the results of the tensile test shown in Table 4, the values of YS, TS, and YR all increase due to bending forming of the plates, but it can be confirmed that all target specifications are satisfied in the product pipes. From the results of the impact test, the toughness value after pipemaking tends to decreases somewhat in comparison with the plates. However, because values exceeding 100 J were secured in all of the pipes, it can be understood that the target specifications could be satisfied

Table 3 Chemical compositions of steel plates

(mass%)

Steel pipe		Plate thickness (mm)	Chemical composition							
			C	Si	Mn	P	S	N	C_{eq}	P_{cm}
TS490-550	P-385B	50	0.13	0.35	1.34	0.006	0.002	0.003	0.38	0.21
	P-400T	95	0.06	0.20	1.48	0.008	0.002	0.005	0.42	0.17
TS570-590	P-440B	80	0.09	0.26	1.50	0.008	0.002	0.003	0.46	0.20
	P-500T	100	0.08	0.24	1.45	0.016	0.003	0.004	0.41	0.19
TS780	P-630T	40	0.06	0.19	2.00	0.012	0.001	0.004	0.55	0.25
	P-630T	60	0.12	0.27	0.97	0.003	0.001	0.005	0.55	0.28

C_{eq}: C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14 P_{cm}: C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/14+5B

Table 4 Mechanical properties of pipes

Steel pipe							Tensile properties (Plate)				Tensile properties (Pipe)			
		D (mm)	t (mm)	t/D	Condition for bending	Heat treatment	YS (N/mm^2)	TS (N/mm^2)	YR5 YS/TS	$_vE_0$ (J)	YS (N/mm^2)	TS (N/mm^2)	YR5 YS/TS	$_vE_0$ (J)
TS490-550	P-385B (Low YR)	800	50	6.3	Cold		434	596	73%	280	499	607	82%	252
		1 000	50	5.0			434	596	73%	280	509	609	84%	243
	P-400T (High YR)	1 300	95	7.3	Warm		405	579	70%	343	564	627	90%	328
		2 100	95	4.5	Cold	Temper	407	586	69%	346	490	609	86%	316
TS570-590	P-440B (Low YR)	900	40	4.4	Cold		502	637	79%	263	535	652	82%	268
		800	45	5.6			479	631	76%	284	572	691	83%	279
		800	50	6.3			467	609	77%	305	550	665	83%	295
		800	60	7.5		Temper	490	645	76%	312	536	667	80%	275
		900	70	7.8		Temper	475	620	77%	298	513	652	79%	271
		1 900	80	4.2			484	658	74%	320	542	672	81%	273
	P-500T (High YR)	1 300	90	6.9	Warm		561	706	79%	210	666	734	91%	150
		2 100	100	4.8	Cold		546	698	78%	231	629	726	87%	223
TS780	P-630T (High YR)	800	40	5.0	Warm		645	841	77%	202	759	833	91%	181
		800	40	5.0			669	823	81%	232	741	862	86%	222
		1 000	50	5.0			662	859	77%	228	775	846	92%	126
		1 000	60	6.0			737	825	89%	254	719	823	87%	250

t/D: Wall thickness/Diameter of steel pipe Tensile test: JIS 2201 No. 12
Charpy impact test: JIS Z 2242 V-notch 1/4t from surface

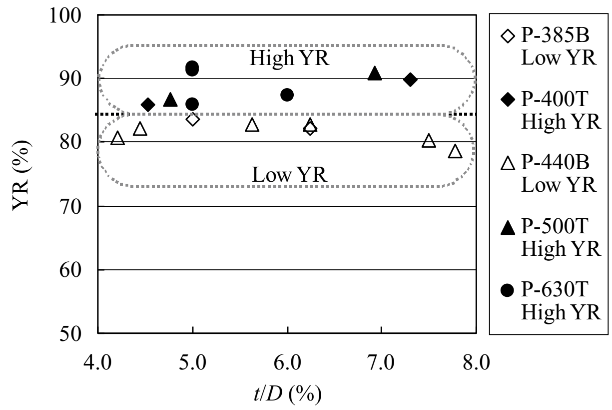


Fig. 6 Relationship of t/D and Yield ratio (YR) for pipe data

irrespective of strength, thickness, or curvature.

Figure 6 shows the distribution of the yield ratio (YR) of the pipes by t/D. In spite of the differences in strength, thickness, and curvature, it is possible to control the value of YR to within the required range, irrespective of t/D, by appropriately controlling the performance of the material plates using the *Super*-OLAC, HOP, and other technologies, and appropriately selecting plate heating during pipemaking or heat treatment after pipemaking.

5. Conclusion

JFE Steel carried out development in order to secure the performance required in steel pipes for building structures in the high strength, heavy wall thickness region of tensile strength (TS) from 490 N/mm^2 to 780 N/mm^2 (YS385 N/mm^2 to 630 N/mm^2) and wall thicknesses of 40 to 100 mm, and confirmed that it is possible to manufacture pipes of the targeted specifications. In particular, it is possible to produce low YR and high YR specification steel pipes with the same strength level in accordance with the customer's requirements. As a result, it is considered possible to supply steel pipes which respond to more diverse design requirements than in the past.

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