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Development of Ultra-high-strength Linepipe, X120

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Abstract

Natural gas is increasingly and greatly important and cost reduction of long distance transportation is essential. High operating pressure and/or small diameter/thin wall linepipes are a means to reduce transmission costs of long distance pipelines. For these challenges, high strength linepipes are required. Nippon Steel has developed an ultra high-strength grade of large diameter linepipe, X120 that far exceeds the conventional grades of X65 and X80 in cooperation with ExxonMobil, the world-biggest major oil&gas company. X120 requires much higher manufacturing technology compared with X65 and X80 and research and development was systematically performed in the fields of material design, steel making, casting, plate production and pipe production (UOE forming and seam welding). The both parties completed the pipe development including small scale commercial production and the evaluation of pipe performance as a linepipe and conducted comprehensive development for pipeline installation such as girth welding technology in a field. Now the commercializing of X120 is confirmed to be possible.

1. Introduction

The importance of natural gas as a source of energy is rapidly increasing, and it is expected to become the principal primary energy source, soon overtaking the position of petroleum. However, since many of important natural gas development fields are located far from large consuming regions, it is necessary to economically transport the gas across a long distance. While the importance of the transportation of liquefied natural gas (LNG) is increasing, pipelines will continue to be responsible for the transport of a significant part of natural gas. In order to reduce the transport costs by long-distance pipelines, many of which extend more than 1,000 km, high operation pressure and use of small-diameter and thin-wall linepipes are effective, and this requires high-strength linepipes[1)].

While the highest-strength grade of linepipes that have so far been brought to commercial application is 5L X80 by the standard of American Petroleum Institute (API), for the purpose of reducing the costs of a pipeline by drastically enhancing the strength of a linepipe,

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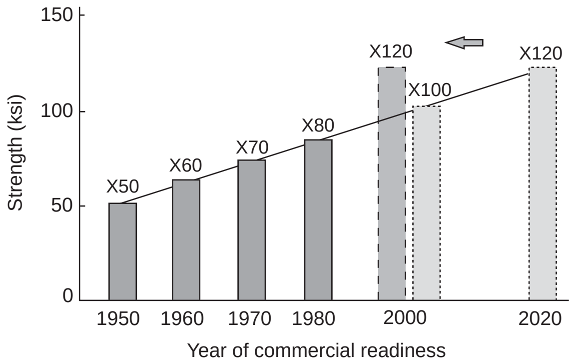

Fig. 1 Evolution of linepipe technology

ExxonMobil and Nippon Steel Corporation have jointly developed an ultra-high-strength large-diameter linepipe, X120. The X120 linepipe was successfully developed while leading steelmakers of the world were pursuing the development and commercial application of X100 linepipes, and the development of the X120 pipe accelerated the strength improvement of linepipes as illustrated in **Fig. 1**[2].

2. Development Targets and Problems to Overcome

The targets at the development of the X120 linepipe are listed in **Table 1**. Since the pipe had to withstand the inner pressure specified for X120 in the API standard, it was necessary that its specified minimum yield strength (SMYS) in the circumferential direction be equal to or higher than 120 ksi (827 MPa)*1). The strength in the longitudinal direction was not specified because it did not directly affect the strength against inner pressure. For the purpose of preventing the initiation of a crack, the Charpy V-notch impact value (CVN value) of a welded seam was specified as a target of low-temperature toughness required of a steel pipe, and for the purpose of arresting the propagation of a crack, should one occur, the ductile-to-brittle transition temperature (DBTT) at a CVN test, the ductile fracture ratio at a Battelle-type drop weight tear test (B-DWTT) and the CVN value were specified as target values for a base metal. The values adopted as tentative targets of the above property items were those obtained by extrapolating the values required of grade X80 or lower under DNV OS-F101 2000, a commonly used pipeline standard. Since the developed linepipe would be used often in cold regions, the required property figures were those at –20°C. It has to be noted that the test temperature was set at –30°C except for the tests using full-thickness test pieces.

An X120 linepipe requires far higher production technology than an X65 or X80 linepipe does, and the research and development activities for the X120 linepipe in all the technical fields such as material design, steelmaking, casting, plate production and pipe production (UOE press forming, seam welding, etc.) had to be organized in an organically integrated manner.

Table 1 Targets of X120 development

Property	Base pipe	Seam weld & HAZ
Tensile strength (TS) (circumferential)	YS ≥ 827MPa (120ksi) TS ≥ 931MPa (135ksi)	TS ≥ 931MPa (135ksi)
CVN energy@–30°C	≥ 231J	≥ 84J
CTOD@–20°C	≥ 0.14mm	≥ 0.08mm
DBTT of CVN	≤ –50°C	
B-DWTT SA@–20°C	≥ 75%	

*1) Under the API standard, the proof stress at 0.5% under-load is used as the yield strength of X80. However, as strength increases, it becomes necessary to use larger under-load values such as 0.6%, 0.7% and so on for correctly measuring yield strength. To avoid the complexity, the proof stress at 0.2% offset was used as the yield strength of X120.

3. Product Development and Its Properties

3.1 Development of plate

The required quantity of linepipes for a pipeline project to which the X120 linepipe is applied is in the order of several hundred thousand to one million tons, and the product has to be produced within a comparatively short period of time. In view of this, the steel plate for the X120 linepipe has to be an as-hot-rolled plate not requiring heat treatment processes, and its production processes have to realize high productivity. Further, since the construction speed of a pipeline is governed by the speed of the girth welding at the construction site, very good weldability is required of the linepipe. For this reason, the steel plate of the X120 linepipe must be of a low-carbon steel that has low sensitivity to cold crack, allow elimination of preheating for welding and be of a high toughness. In order to realize high strength with a low-carbon steel, it is necessary to make the most of transformation strengthening. Following the above reasoning, microstructures with which high strength and high toughness could be obtained were studied.

Steel plates of different chemical compositions were experimentally produced through different manufacturing processes using laboratory equipment and were examined. As a result, it was found that satisfactorily high strength and toughness (an initial target value of a CVN value of 120 J or higher at –30°C) could be obtained with a low-carbon bainitic structure. Extremely high CVN values can be obtained especially with a lower-bainitic structure as seen in **Photo 1**. With an upper-bainitic structure, coarse martensite austenite constituents (MAs) as shown with an arrow in the photo exist, and the

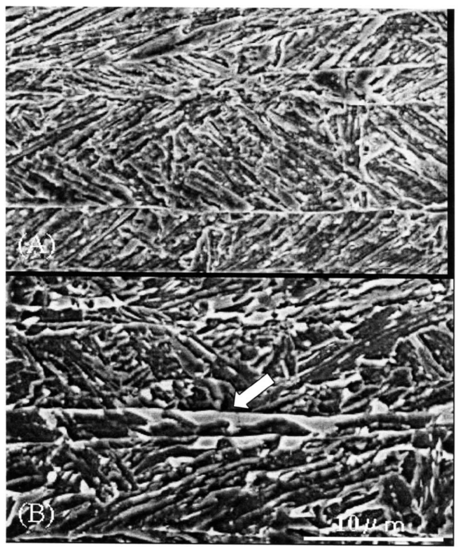

Photo 1 Effect of microstructure on CVN value (microstructure, IDQ stop temperature, CVN value at –40°C)
(A) Lower bainite, 453°C, 258J, (B) Upper bainite, 533°C, 167J

substructures of packets are coarser than those of a lower-bainitic structure, and for this reason, the CVN value tends to be low. In order to obtain the bainitic structure, the interrupted direct quenching (IDQ) process, which is schematically illustrated in **Fig. 2**, was employed, and rolling and cooling conditions and the IDQ stop temperature were specially selected so as to stably realize a fine lower-bainitic structure.

In the study of steel chemistry, initially, both boron (B) steels and B-free steels were considered. Although the authors knew that historically B steels were little acceptable as the linepipe, their properties were found to be far superior to other kinds of steels within the content ranges of alloying elements generally permitted for a linepipe. For the above reason, a B steel was finally selected as the material of the X120 linepipe. Ti was added to the B steel by an amount sufficient for completely stabilizing N, and also Mo so as to make the most of the hardenability improvement effect of B[3]. The strength-toughness balance of the steel plates experimentally produced at a heavy plate mill is shown in **Fig. 3**; B steels exhibited higher CVN values than B-free steels did. Extremely high toughness was obtained with B steels having especially low C contents.

Fig. 4 shows the relationship between the CVN values and the values of hardenability index β of specimens that underwent a heat cycle to simulate a coarse-grain heat affected zone (HAZ) of a welded joint. In order to produce a steel plate for an X120 linepipe, it is necessary to control steel chemistry so that the hardenability index β is roughly 3 or higher. It is clear from the figure that, in the above range of β, the CVN values of B steels are higher than those of B-free steels. The micro-structure of the coarse-grain HAZs of the B steels that showed high CVN values consisted mainly of lower bainite.

The strength of a lower-bainitic steel is nearly equal to that of martensitic steel of the same chemical composition. As is well known, the strength of martensite is determined by the content of C, and for this reason, the strength of an X120 steel plate depends largely on its C content. The relationship between the tensile strength and C content of X120 is shown in **Fig. 5**. The same of X80 and X100 are also given for reference purposes. Whereas the C-content dependence of tensile strength is small in grade X100 and lower, the strength of X120 is substantially proportional to C content and is very close to maximum strength (the strength of martensite). Since the strength of the base metal is close to maximum hardness, it is inferred that cold crack does not occur to a HAZ. In fact, as seen in **Fig. 6**, no weld crack occurred to the specimens of y-groove weld crack tests by gas

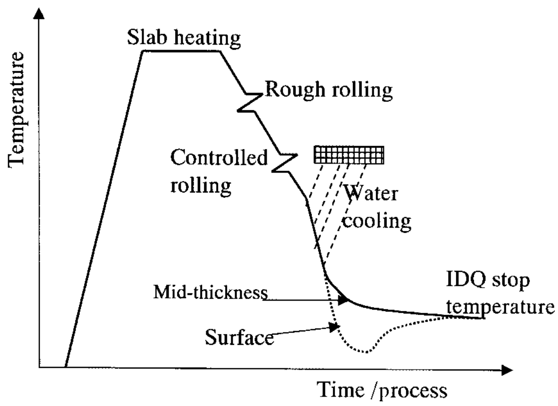

Fig. 2 Schematic illustration of IDQ process

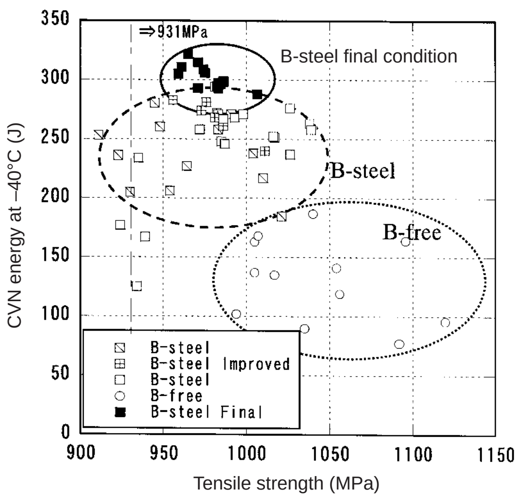

Fig. 3 Effect of alloy system on the balance of tensile and CVN value

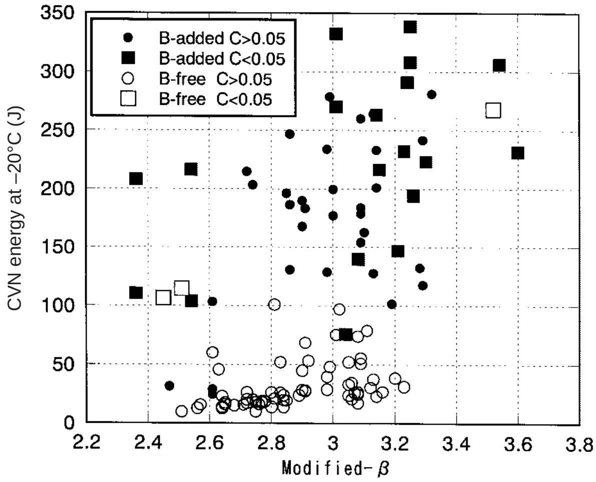

Fig. 4 Effect of hardenability index, β on HAZ toughness (CVN value)

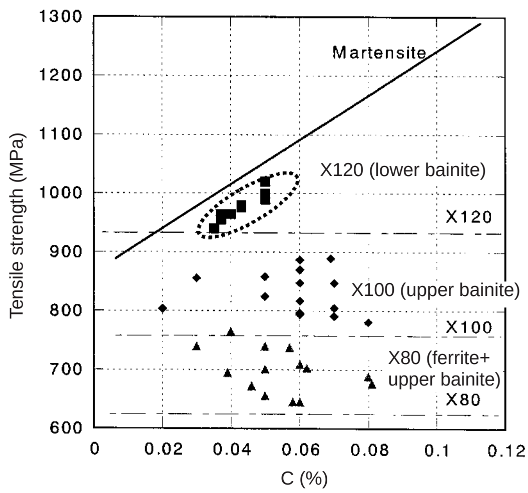

Fig. 5 Relationship between C content and tensile strength for high strength linepipe

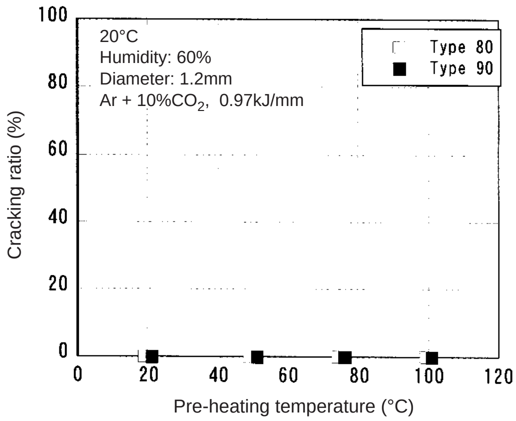

Fig. 6 Cold cracking sensitivity of girth weld - results of y-groove weld cracking test

metal arc welding (GMAW) without pre-heating. It is presumed that, with a steel having a lower-bainitic structure such as the X120 steel, weld crack sensitivity is strongly influenced by C content.

On the basis of the above results, a low-C-high-Mn-Mo-Ti-B steel has been developed, and a tensile strength as high as 931 MPa or more and a high toughness have been realized for the first time with an as-hot-rolled heavy steel plate of the developed steel. In order to meet the target strength in mass production, it was necessary to control the C content at the steelmaking process within a narrower range than in usual commercial practice, and the technology to carry this out has also been established.

3.2 Development of seam welding technology

In order that as many of the existing production facilities as possible could be used for the production of the X120 linepipe, the submerged arc welding (SAW) method with one pass each for the inside and outside welds, which had been employed for conventional grades of linepipes, was adopted also for the seam welding of the X120 pipe.

Since a strength equal to or higher than that of the base metal was required of the weld metal of the seam welding, any conventional welding materials could not be used for the X120 pipe, and therefore, new high-strength and high-toughness welding materials for SAW were developed. Generally, the strength and toughness of a weld metal are incompatible with each other; the higher the strength, the lower the toughness becomes. **Fig. 7** shows the relationship between the strength and toughness of SAW weld metals obtained with different combinations of welding wires and fluxes that were experimentally produced. Each of the points in the diagram represents a combination of a welding wire, a flux and a specific welding condition, and the toughness value is the average value of three test pieces for each of the combinations. Generally speaking, toughness tends to decrease as strength increases, and this is the same with SAW weld metals having a 1,000-MPa class tensile strength.

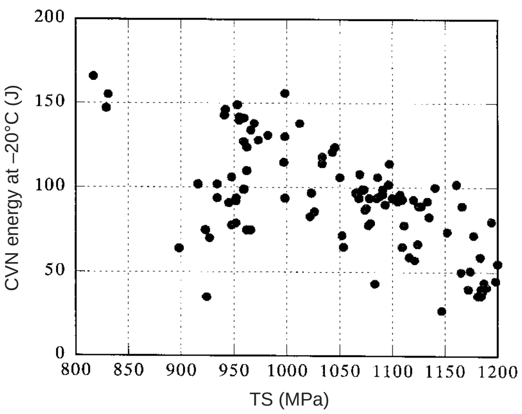

Fig. 7 Relationship between tensile strength and CVN value of submerged arc weldmetal

However, the values of toughness of weld metals having the same tensile strength were dispersed rather widely as seen in Fig. 7. Therefore, it was possible to obtain a weld metal that realized the combination of target strength and toughness, namely a strength of roughly 1,000 MPa and a high toughness over 84 J, by appropriately designing the chemistry of weld metal and properly selecting welding wire and flux. The structure of the weld metal thus obtained consisted of upper bainite. On the basis of the test results described above, a welding wire and flux excellent in welding workability for obtaining a high-strength and high-toughness weld metal have been developed. The HAZ toughness of a welded seam is improved as the heat input of welding decreases, and for this reason, the condition of the seam welding of the X120 pipe was set such that the heat input was lower than in the cases of conventional grades. In this relation, a new welding technology covering an optimum groove shape and welding condition was developed. As a result of the welding materials and technology thus developed, a high-toughness welded seam having the same strength as that of the base metal has been attained.

3.3 Development of pipe forming technology

The principal challenge in the development of the UOE press pipe forming technology for the X120 linepipe was how to overcome large spring back, a problem common to high-strength materials. The problem of the spring back at pipe forming was tackled from an early stage of the X120 development project employing finite element analysis (FEA) and plant tests in combination.

When an X120 plate is formed in the same manner as an X65 plate is, for example, the upper end opening after the U press becomes so large that the U-shaped plate cannot be inserted into the upper die of the subsequent O press. In addition, the range of conditions to obtain a pipe having satisfactory roundness is extremely narrow. All the steps of the UOE press forming processes were simulated by the FEA, and an appropriate forming condition was identified and suitable forming tools were developed. As a result, it has been made possible to produce an X120 linepipe satisfying the target roundness.

3.4 Test production and properties of product pipe

The development of the X120 linepipe was carried forward through the development of the technologies described above and in parallel from an early stage, many times of test production using commercial plant equipment for identifying problems in the actual production of the pipe. The test production was carried out using steel plates 14 to 20 mm in thickness to form pipes 28 to 36 in. in outer diameter.

Table 2 shows examples of the chemical compositions of the material plates and weld metals of the seam, and **Table 3** those of the mechanical properties of the pipes.

Through ring expansion tests, the strength of the pipe in the circumferential direction was confirmed to be well over 100% of the SMYS. The tensile stress-strain curve of the pipe in the longitudinal direction is plotted in **Fig. 8**. The uniform elongation of the pipe is about 3%, which indicates that the pipe has good enough plastic deformability to meet the requirements in most pipeline design.

Table 2 Typical chemical compositions of plate and seam weld

(mass%)

	C	Mn	Mo	Ti	B		P_{cm}
Plate	0.041	1.93	0.32	0.020	0.0012	Others	0.21
	0.036	1.96	0.34	0.017	0.0012	Others	0.21

	C	Si	Mn	Ni	Mo	Cr	P_{cm}
OW	0.05	0.23	1.63	2.2	0.92	1	0.31
IW	0.05	0.18	1.69	2.6	0.98	1.1	0.32

OW: outside weld, IW: inside weld

The ductile-to-brittle transition temperatures (DBTTs) of CVN test of all the base metals were well below –50°C, and the CVN values at –30°C met the target value. Although the percentage ductile fracture of the B-DWTT did not clear the development target value, it was not considered to be a problem because the fracture mode at gas burst tests was ductile and the crack propagation speed was confirmed to be about 300 m/s at the maximum, which was sufficiently lower than the depressurization rate of the gas[4)].

The properties of weld metal meet the target values, and the toughness of a HAZ is high at the position 2 mm from the intersection of the fusion lines (FLs) of outside and inside seam welds, which position corresponds to a coarse-grain HAZ. However, low toughness values were observed at 1 mm from the intersection of the FLs, which position may hit a local brittle zone. Facing the fact, evaluation based on fracture mechanics was carried out to evaluate the characteristics of the pipe at real fracture. Required crack tip opening displacement (CTOD) was calculated on an assumption of the existence of a surface-breaking crack 2 mm in depth at a seam weld toe and possible shape irregularity and stress distribution. As a result, it was concluded that a CTOD of 0.08 mm or more was good enough. Since a defect equal to or larger than 2 mm is detected at a non-destructive inspection and an internal defect up to 4 mm in width will be permissible under the same value of critical CTOD, the above CTOD is considered to be a target value very much on the safety side. The CTOD values of the brittle portions of weld metals and HAZs are plotted in **Fig. 9**; all the CTOD values are well above the least required CTOD value of 0.08 mm. Judging from Fig. 9, the seam weld has sufficiently high resistance to crack initiation and is suitable for use at –20°C.

Fig. 10 shows the results of hydraulic burst tests of individual pipes converted into normalized values using the thin-wall cylinder

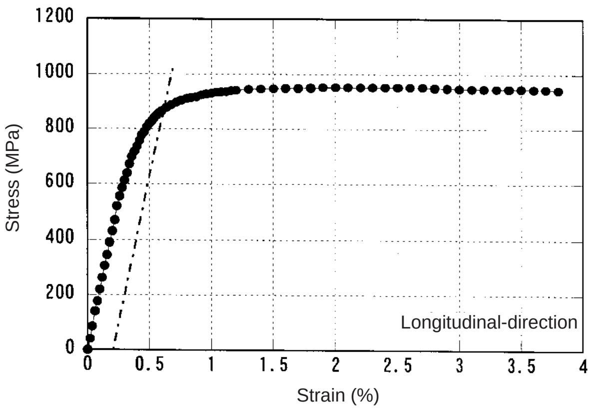

Fig. 8 Typical stress-strain curve in the longitudinal direction

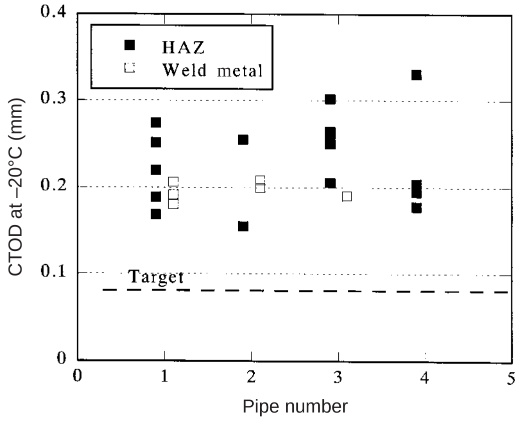

Fig. 9 CTOD test results of the seam weld centerline and heat affected zone

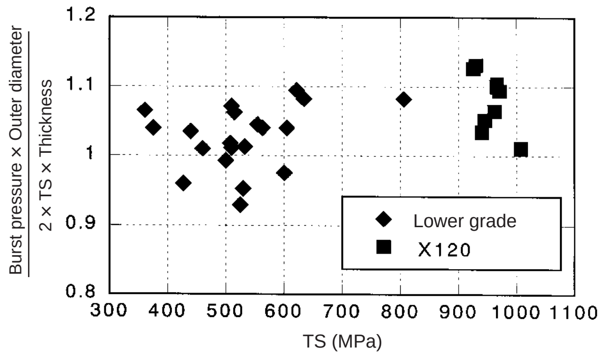

Fig. 10 Burst pressure as a function of tensile strength

Table 3 Examples of mechanical properties of pipes

	Tensile test*[1]								Trans-weld	Charpy V-notch					B-DWTT	
	Circumferential				Longitudinal					J (average of 3 specimens)					Shear area (%)	
	YS (MPa)	TS (MPa)	El*[2] (%)	YS/TS (%)	YS (MPa)	TS (MPa)	El (%)	YS/TS (%)	TS (MPa)		Base metal	Weld metal	FL+ 1mm*[3]	FL+ 2mm*[3]		Base metal
Pipe 1	897	974	25	92	905	938	27	96	941	0°C	287	200	228	249	0°C	64, 65
										–30°C	287	178	126	172	–20°C	62, 59
Pipe 2	920	1,017	24	90	911	981	23	93	988	0°C	287	172	156	226	0°C	88, 81
										–30°C	290	167	43	106	–20°C	90, 79

*[1] API strap specimen, *[2] Elongation, *[3] Distance from the intersection of the SAW

formula[4]. The normalized values of all the tested X120 pipes exceeded one, and the results were superior to those of lower-grade pipes. The property of the X120 pipe to withstand internal pressure was thus confirmed.

3.5 Development of related technologies

Practical viability of girth welding at a pipeline construction field is essential for actual use of the X120 pipe. In the joint development framework, ExxonMobil was responsible for the development of welding wire for GMAW and the establishment of welding technologies, and these have been brought into practical applicability[5].

On the other hand, Nippon Steel also developed a pipe bend by high-frequency heating. Cold bending of the X120 pipe was also tested and bending at a point by 2° was achieved successfully. Since this bend angle exceeds the angles permitted under many pipeline codes, the developed pipe was confirmed to have a sufficient bending capability for field deformation.

4. Production Tests

For the purpose of identifying problems in the commercial production of the developed pipe, about 300 pieces of the X120 pipe with 36 in. in outer diameter and 16 mm in wall thickness were produced at a commercial production plant. Optimum manufacturing conditions were established through the test production, and product property distribution data were collected at the same time. **Fig. 11** shows the results of tensile tests in the circumferential direction using full-thickness test pieces; all the results met the target values.

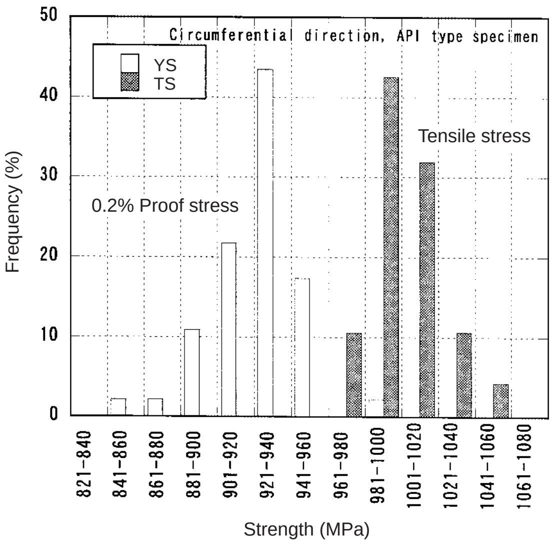

Fig. 11 Distribution of YS and TS for pipes manufactured in a small scale commercial production

Other tests were carried out and the results were substantially the same as those described in sub-section 3.4. The tests for establishing the technologies of field construction work and welding were also carried out using the test-produced pipes, and data of product properties and work efficiency were collected. It is expected that the pipe manufacturing conditions will be further refined and the product properties enhanced and stabilized when the developed product is actually produced commercially.

5. Closing

An ultra-high-strength linepipe API 5L X120, far superior to conventional grade products, has been developed. Significantly more advanced production technology than is required for X65 or X80 is required for the manufacture of the X120 pipe. To realize this, research and development activities in all the fields such as material design, steelmaking, casting, plate production and pipe production (UOE press forming and seam welding) were carried out in an organically integrated manner. The development of the pipe including a small-scale test of commercial production has been completed, and the performance of the pipe at field use for pipeline construction has been evaluated. Related technologies such as the technology of girth welding at a construction field have been brought into actual applicability. Thus, through the comprehensive technical development and tests, the X120 linepipe has proved to be commercially applicable.

Acknowledgement

The ultra-high-strength linepipe X120 was developed through joint research with ExxonMobil; thus, not only the performance of the new pipe product and the developed related technologies but also the basic technologies for manufacturing the pipe are the fruits of the joint development of both the companies. Messrs. J. Y. Koo, N. V. Bangaru, M. J. Luton, D. P. Fairchild, M. L. Macia, S. D. Papka, C. W. Petersen and many other people of Research and Development Division of ExxonMobil greatly contributed to the success of the development. In addition, at the early stages of the development project, Dr. Hiroshi Tamehiro, professor of Chiba Institute of Technology (then Chief Researcher at Steel Research Laboratories) significantly contributed to the success of the development.

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