KAWASAKI STEEL TECHNICAL REPORT
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Shigehiko Yoshimura, Kenichi Amano, Takashi Uemura, Hiroshi Nishizaki, Yoshiyuki Saito, Makoto Sekizawa

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A steel was developed and applied to the production of plates for UOE line pipes which are used to transport sour oil in the North Sea. The steel plates 22.2 to 38.1 mm thick were made of API 5L-X60 and weigh 50 000 tons in total. The most critical and the most difficult requirements to be met follow: The PCM which is an indicator of the susceptibility to weld cracking should be as low as 0.150% for plates 22.2 and 23.8 mm thick. These requirements were unable to be satisfied by the ordinary manufacturing process. Only the thermomechanical control process (TMCP) and the fine steel making process were able to do it. The present paper describes the details of the steel plate manufacturing processes and the properties obtained.

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Development and Manufacture of Low P_{CM}, High Toughness Steel Plates for API 5L-X60 UO Pipe*

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A steel was developed and applied to the production of plates for UOE line pipes which are used to transport sour oil in the North Sea. The steel plates 22.2 to 38.1 mm thick were made of API 5L-X60 and weigh 50 000 tons in total. The most critical and the most difficult requirements to be met follow: The P_{CM} which is an indicator of the susceptibility to weld cracking should be as low as 0.150% for plates 22.2 and 23.8 mm thick. These requirements were unable to be satisfied by the ordinary manufacturing process. Only the thermo-mechanical control process (TMCP) and the fine steel making process were able to do it. The present paper describes the details of the steel plate manufacturing processes and the properties obtained.

1 Introduction

Large-diameter line pipe for the transport of oil and natural gas has been produced for more than ten years. Production of this pipe has increased with the growth in demand for energy, and Kawasaki Steel has been among the leaders in this field.

Most steel plates for line pipe are produced by controlled rolling. Over the past decade, performance requirements for pipe have turned so strict as to include higher strengths through an increased wall thickness to cope with higher transporting pressures, higher toughness for services in low-temperature districts, and improved corrosion resistance for the transport of sour gas. In meeting these demands, remarkable progress has been made in plate manufacturing techniques using controlled rolling.[1-3] Furthermore, submarine line pipe laid in cold environments such as the North Sea must have excellent on-site weldability, and it has become important to control the carbon equivalent and the index of weld cracking susceptibility (P_{CM}) to low values.

With progress in steelmaking techniques, it has become possible to produce very clean and pure steels and to control chemical composition to within very narrow ranges. Progress in plate rolling techniques has made it possible to improve weldability and toughness through a reduction of carbon content, which is accomplished by effective application of the thermomechanical control process, TMCP, for the control of transformation structure. TMCP involves controlled rolling and accelerated cooling, and is termed MACS, Multipurpose Accelerated Cooling System, in Kawasaki Steel's process.

On the basis of such technical progress, the company received orders for and produced about 50 000 t of line pipe for the submarine transportation of oil in the North Sea. Offshore line pipe, which accounts for 90% of the quantity, was of 22.2 and 23.8 mm in wall thickness. The

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* Originally published in *Kawasaki Steel Giho*, **18**(1986)4, pp. 307-313

P_{CM} of the offshore line pipe was limited to 0.150 or less from considerations of weldability because it was to be laid from laying barges at sea. Limitations in chemical composition were somewhat relaxed for the 38.1-mm thick buckle arresters to be attached to line pipe nodes because 22.2 or 23.8-mm thick skirt pipe is sometimes attached to the buckle arresters in the shop. Limitations in chemical composition were also somewhat relaxed for the 27.0 and 30.2-mm thick on-land line pipe.

This report describes the examination conducted into manufacturing conditions for the plates for this line pipe, as well as the results of production.

2 Examination of Plate Manufacturing Conditions

2.1 Required Performance

Plates for the submarine line pipe in this project are required to meet not only the API 5L standard, but also satisfy the following requirements in terms of pipe laying and service environment:

(1) The pipe was required to be layable without preheating or postweld heating on the laying barge.

(2) Excellent HIC resistance and SCC resistance were required, as the pipe in this project was intended for transport of sour gas.

(3) To ensure the stable production of a large quantity, 50 000 t, of plate for pipe by the controlled rolling and accelerated cooling method, minimal variation in mechanical properties of the plate and excellent shape after cooling were required.

Plate specifications are shown in **Table 1**.

Table 1 Specifications (for pipe)

Tensile Properties*			Impact	DWTT	Hardness at welded joint (HV)	HIC (BP sol.)	P_{CM}**
YS (MPa)	TS (MPa)	El (%)	$_vE_{-20}$ (Joule)	$SA_{0^\circ C}$ (%)			
414 ≀ 516	517 ≀ 647	≥ 29	Av. ≥ 42 Any ≥ 30	≥ 75	≤ 248	CSR = 0%	≤ 0.150 (22.2, 23.8 mm) ≤ 0.160 (27.0, 30.2 mm) ≤ 0.180 (38.1 mm)

* For both L and C directions

** $P_{CM} = C + \frac{Mn + Cr + Cu}{20} + \frac{Si}{30} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B$

2.2 Concept of Composition Design

The task in composition design was to obtain sufficient strength in spite of the low P_{CM}, low C, and low Mn contents required to ensure weldability, HIC resistance, and SCC resistance. To produce such a large quantity of plate stably, it is necessary to use composition design to reduce the variation in mechanical properties caused by changes in accelerated cooling conditions. The composition design in this case embodied the following concepts:

(1) To realize welding without preheating and postweld heating and to obtain excellent HIC resistance and SCC resistance, it was necessary that the design meet the requirements of ultralow P_{CM} (0.150% or less for plate thicknesses of 23.8 mm or less), low Mn content (1.20% or less for plate thicknesses of 23.8 mm or less), ultralow P content (80 ppm or less), and ultralow S content (15 ppm or less).

(2) Variations in mechanical properties resulting from changes in cooling conditions were reduced by lowering the martensite formation temperature, which was accomplished by promoting ferrite transformation at high temperatures through a reduction in the C and Mn contents, raising the C level in the retained austenite portion, and thus stabilizing the austenite phase.

(3) To compensate for the decrease in strength resulting from decreased P_{CM} values and C and Mn contents, Cu, Ni, Nb, Ti, and V are added in combination and Mo was further added as required.

An experiment was conducted using a model rolling mill and model cooling device to investigate the dependence of the tensile strength of a low-C low-Mn steel on the finish cooling temperature in accelerated cooling. A comparison between the results obtained and those obtained with three other types of steel is shown in **Fig. 1**. The variation in strength due to changes in the finish cooling temperature in the vicinity of 450°C is very small because the martensite formation temperature range shifts downward by about 100°C due to the reduction in C and Mn contents.

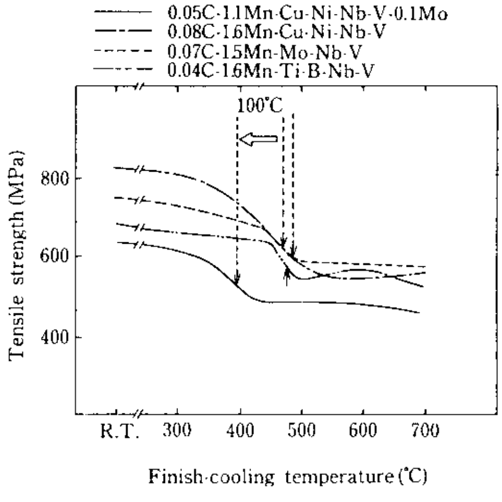


Fig. 1 Comparison of tensile strength-finish cooling temperature dependence of low Mn steel with those of high Mn steels

2.3 Controlled Rolling and Accelerated Cooling

To obtain the required performance in such a low C-low Mn-Cu-Ni-Nb-V-Ti-(Mo) steel as described above, it is necessary to optimize reheating, rolling, and cooling conditions. The effects of controlled rolling and accelerated cooling are summarized as follows:

(1) Reheating Conditions

The slab was reheated to a temperature at which the carbides and nitrides of Nb, Ti, and V would dissolve completely. Strength was increased by causing these carbides and nitrides to precipitate in fine grains during rolling and cooling. To obtain low-temperature toughness, however, the upper limit of the slab reheating temperature was set so as to prevent the coarsening of initial austenite grains. The effect of slab reheating temperature on yield strength, tensile strength, and 50% shear fracture appearance transition temperature is shown in **Fig. 2**. The upper limit of the slab reheating temperature was held to 1 180°C because strength increases with no decrease in toughness up to this temperature.

(2) Rolling Conditions

The reduction ratio for the recrystallization region was set at more than 65% to increase the number of ferrite nucleation sites by introducing lattice defects into the austenite aimed at the refinement of ferrite grains and to promote ferrite transformation by raising the transformation start temperature (Ar_3). On the other hand, the reduction of the dual-phase region was limited to 30% or less from the viewpoint of HIC resistance, and conditions not requiring rolling of the dual-phase region were given priority. When the finish rolling temperature drops, transformation proceeds rapidly before the start of cooling, resulting in insufficient strength of the plate. The effect of the finish rolling temperature on strength and toughness is shown in **Fig. 3**. Setting the lower limit of the finish rolling temperature, i.e. the start cooling temperature, at about Ar_3 is most effective in obtaining high toughness.

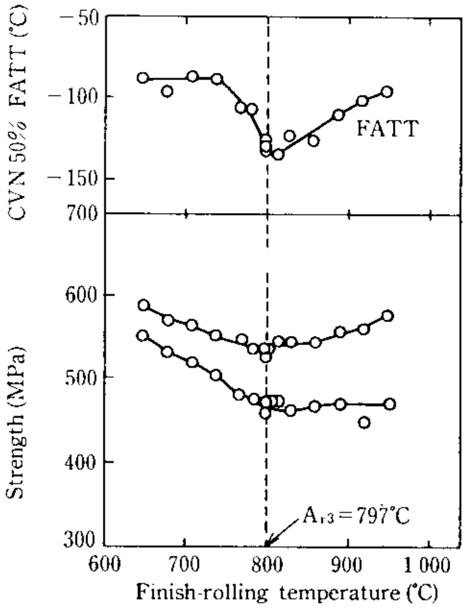


Fig. 3 Change in mechanical properties with finishing-rolling temperature

(3) Cooling Conditions

The lower limit of the cooling rate and the upper limit of the finish cooling temperature were set so as to obtain a fine ferrite plus fine bainite structure

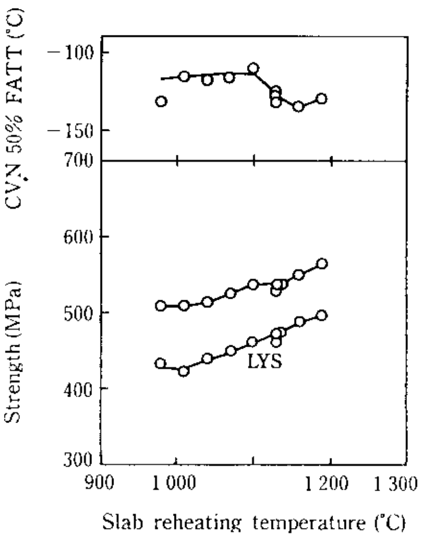


Fig. 2 Change in mechanical properties with slab reheating temperature

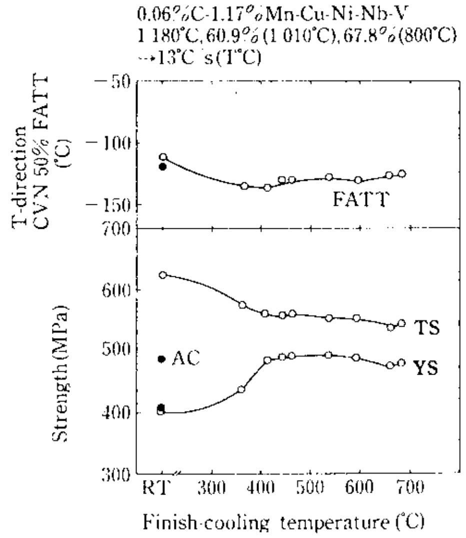


Fig. 4 Change in mechanical properties with finishing-cooling temperature (Mo-free steel)

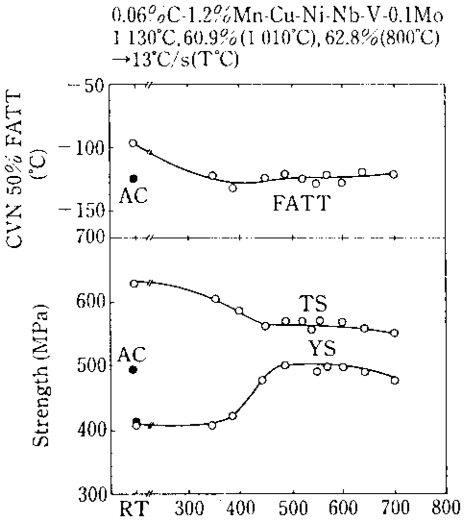


Fig. 5 Change in mechanical properties with finishing-cooling temperature (Mo-bearing steel)

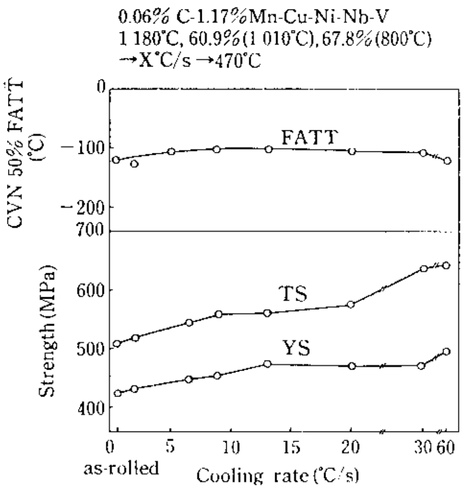


Fig. 6 Change in mechanical properties with cooling rate (Mo-free steel)

after cooling. The effect of the finish cooling temperature on the 50% shear fracture appearance transition temperature, yield strength, and tensile strength is shown in **Figs. 4 and 5**. In both the Mo-free steel and Mo-bearing steel, strength and toughness are very stable in the finish cooling temperature range around 450°C. The effect of the cooling rate on strength and toughness is shown in **Figs. 6** and 7. It is apparent that variations are very small in the cooling rate range from 13 to 20°C/s.

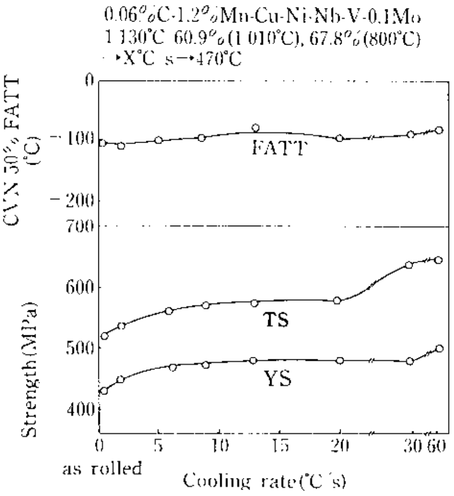


Fig. 7 Change in mechanical properties with cooling rate (Mo-bearing steel)

3 Manufacture of Steel Plates

3.1 Manufacturing Conditions

Based on the results obtained using a model rolling mill in the research stage described above, an examination was made into the chemical composition and manufacturing conditions required with an actual rolling mill.

The manufacturing process for the steel plates is shown schematically in **Fig. 8**. Because, in order to obtain HIC resistance and SSC resistance, it was necessary to produce an ultralow-P, ultralow-S steel with a P

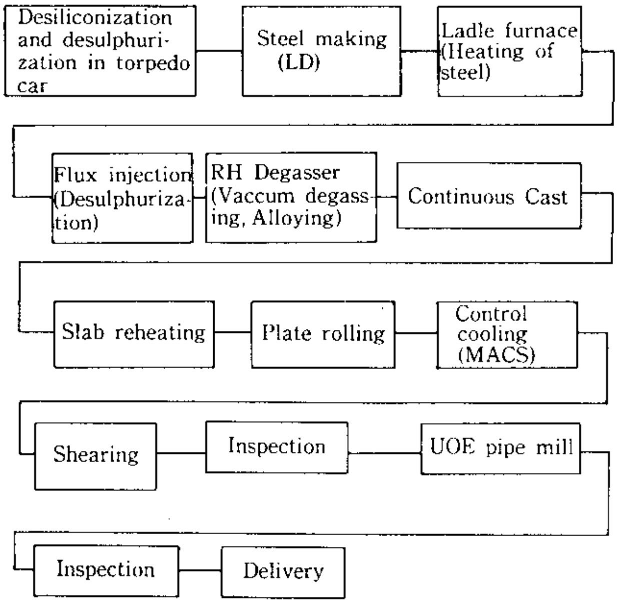


Fig. 8 Manufacturing process

Table 2 Chemical composition (Aiming) (wt%)

Thickness	C	Si	Mn	P	S	Others	P_{CM}
22.2 mm, 23.8 mm	0.06	0.25	1.17	≤0.008	≤15 ppm	V, Nb, Ti, Al, Ca	0.147
27.0 mm, 30.2 mm	0.06	0.25	1.20	≤0.008	≤15 ppm	V, Nb, Mo, Ti, Al, Ca,	0.155
38.1 mm	0.07	0.25	1.30	≤0.008	≤15 ppm	V, Nb, Mo, Ti, Al, Ca	0.171

content of 80 ppm or less and an S content of 15 ppm or less, the LF (ladle furnace)-FI (flux injection)-vacuum degassing process was adopted for secondary refining.

As chemical compositions, an Mo-free steel was selected for plate thicknesses of 22.2 and 23.8 mm and Mo-bearing steels were selected for plate thicknesses of 27.0 mm or more. The target chemical compositions of these steels are shown in **Table 2**. With Mo-free steel, it is necessary to raise the slab reheating temperature to obtain strength; however, toughness, especially the drop-weight-tear-test (DWTT) characteristic, deteriorates as the reheating temperature increases. Therefore, in consideration of a balance of the two properties, the reheating temperature was controlled within a narrow, ±5°C range. The finish rolling temperature was set in the vicinity of the Ar_3 point to obtain HIC resistance with minimal rolling in the dual-phase region. **Figure 9** shows the correlation between the start cooling temperature and the tensile strength obtained in an actual rolling mill when rolling was completed in the vicinity of this Ar_3 point and accelerated cooling was then conducted. As is apparent from this figure, the transformation time of polygonal ferrite becomes shorter and tensile strength increases with higher start cooling temperatures. This tendency seems to be especially marked with low-C, low-Mn steels such as the present one, where the frequency of nucleation of ferrite in the period between the end of rolling and the start of cooling and the rate of ferrite growth are both high. On the other hand, the DWTT characteristic tends to deteriorate with higher finish rolling temperatures. The DWTT characteristic apparently deteriorates because the separation due to rolling in the dual-phase region does not occur. Therefore, it is also necessary to control the finish rolling temperature within a very narrow range with the Ar_3 point as its center in consideration of the balance between strength and the DWTT characteristic.

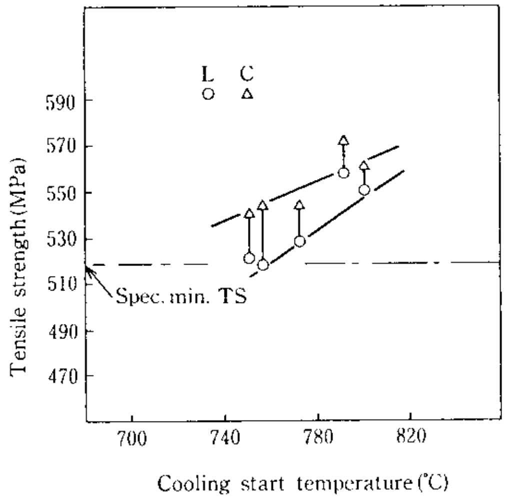


Fig. 9 Correlation between cooling start temperature and tensile properties

Since the addition of Mo made it relatively easy to obtain strength in the plate of Mo-bearing steel 27 to 38 mm in thickness, a good DWTT characteristic was ensured by lowering the slab reheating temperature. As with the Mo-free steel, the finish rolling temperature was controlled within a range with the Ar_3 point at its center in consideration of the balance among HIC resistance, strength, and toughness.

Further, to guarantee stable production of the large quantity of 50 000 t of pipe-use plate under strict time limitations, it was necessary to reduce variations in mechanical properties and ensure excellent post-cooling plate shape. To this end, a control model was used and fully automatic operation was carried out by a combination of process computers. The control model is composed of three functions: a mechanical property control model,[4] a plate temperature prediction model,[5] and a uniform cooling model.[5] Optimum conditions for producing high-quality plates with uniform mechanical properties were ensured using this control model. The

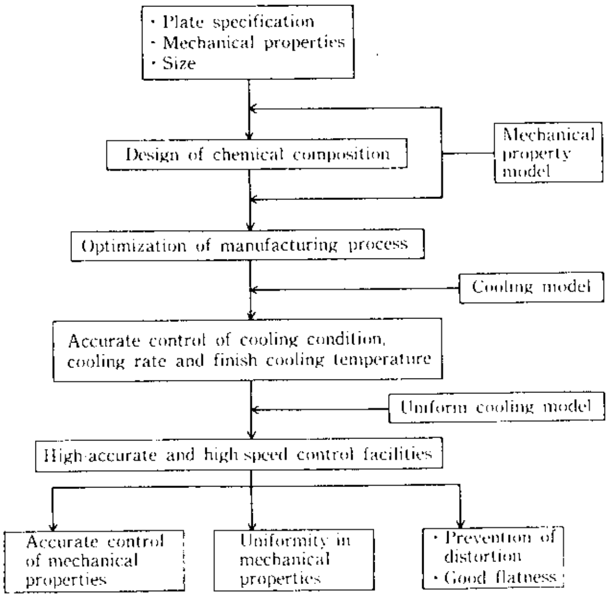


Fig. 10 Block diagram of on-line control model for mechanical properties

configuration of the system for controlling mechanical properties with this model is shown in **Fig. 10**.

3.2 Results of Manufacture of Steel Plates

Actual chemical compositions of plates 22.2 and 23.8 mm in thickness are shown in **Fig. 11**. P_{CM} is within the range from 0.138 to 0.150 and is controlled with very high accuracy. **Figures 12** and **13** show the mechanical properties of plates 22.2 and 38.10 mm in thickness, respectively. The results completely meet the required specifications and show only minor variations. These results are considered to be due to the successful control of variations in chemical analytical values and the fact that the chemical composition of this steel is not significantly affected by the finish cooling temperature. Results of an investigation of the strength distribution of the 22.2-mm thick plates are shown in **Fig. 14**. Variations in strength within individual plates were minor, and were about 2 kgf/mm^2 at the maximum. Accordingly, it was ascertained that under the manufacturing conditions for this type of plates, the variations of characteristic values in individual plate and among plates were very small. **Photo 1** shows microstructures of a 22.2-mm thick Mo-free plate and a 38.1-mm thick Mo-bearing plate as observed by optical microscope. Both show a homogeneous ferrite-bainite structure.

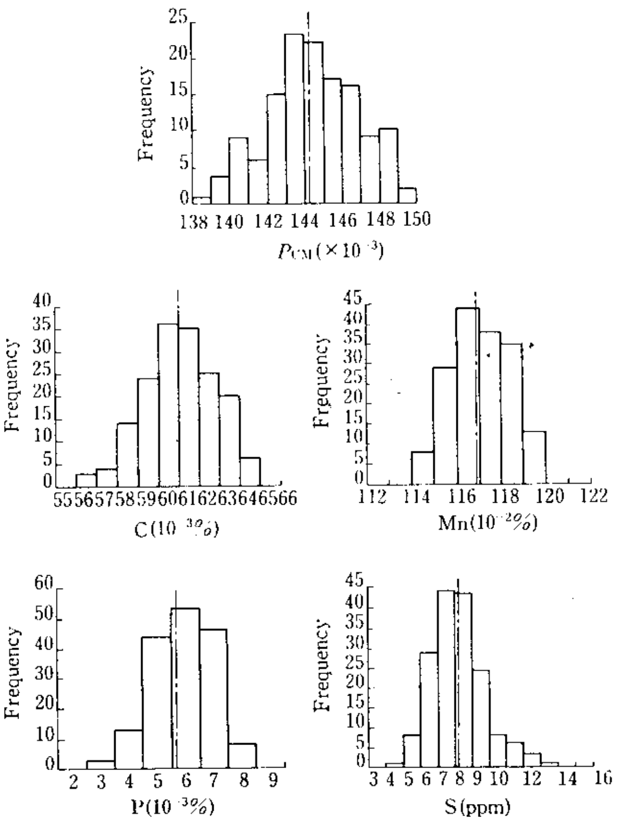


Fig. 11 Actual data of chemical composition (22.2 mm and 23.8 mm thick)

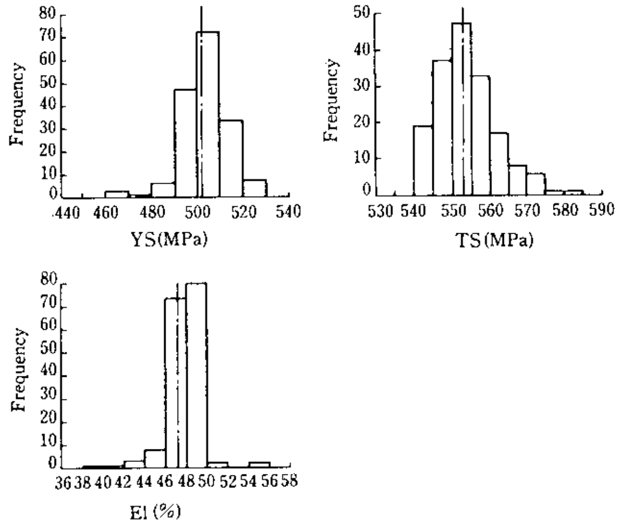


Fig. 12 Actual data of mechanical properties (22.2 mm thick)

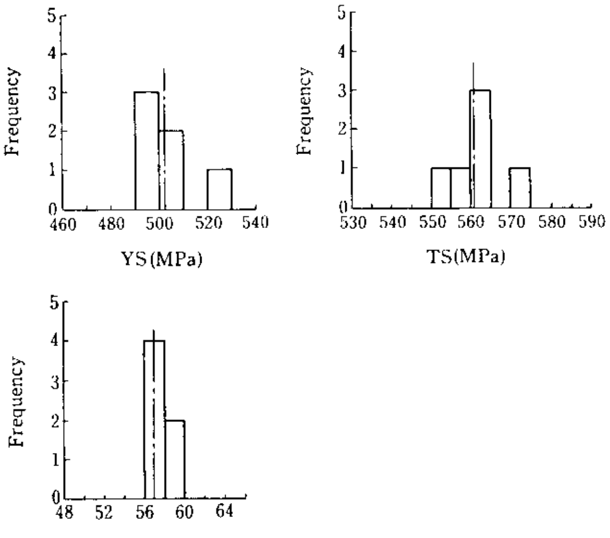


Fig. 13 Actual data of mechanical properties (38.1 mm thick)

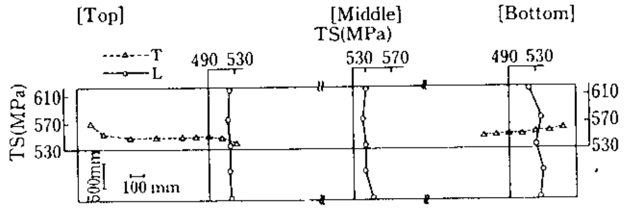
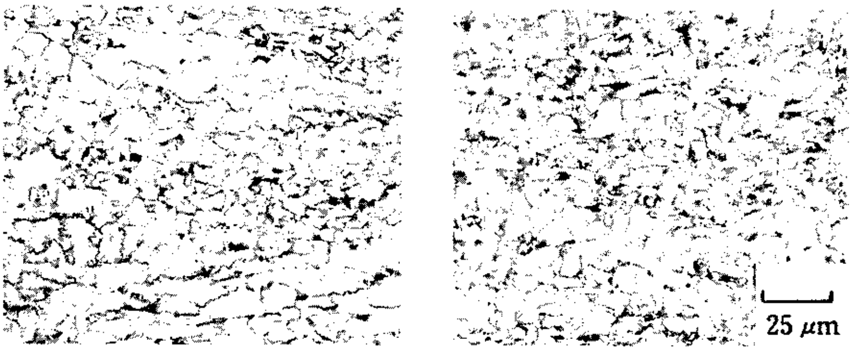


Fig. 14 Distribution of tensile strength



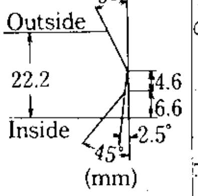
Mo free steel Mo bearing steel

Photo 1 Microstructure

4 Results of Pipe-Making

Pipe-making by the UOE process was conducted at the large-diameter pipe mill at Chiba Works. Welding materials (wire and flux) for four-electrode submerged arc welding with an internal and an external layer were newly developed and used for this project in order to ensure the strength and toughness of the weld metal itself, as well as to maintain appropriate hardness values (HV ≦ 248) after the formation of girth welds by MIG welding with relatively low heat input. The groove geometry and welding conditions employed are shown in **Table 3**. The mechanical properties of the 22.2-mm thick pipe manufactured are shown in **Figs. 15, 16,** and **17** as an example. Mechanical properties of the pipe show very small variations and are stable, as in the case with the plate, and meet the required specifications. This steel pipe was produced as offshore line pipe for sour gas service and was mainly 714.4 mm in outside diameter, 22.2 mm in wall thickness, and 11.9 to 12.5 m

Table 3 Joint geometry and welding condition (22.2 mm thick)

Joint geometry	Welding condition					
		Elect-rode	Current (A)	Voltage (V)	Speed (m/min)	Heat input (kJ/cm)
	Outside	1	1 030	35	1.47	48.1
		2	860	38		
		3	720	38		
		4	570	38		
	Inside	1	1 130	35	1.47	52.7
		2	960	38		
		3	790	38		
		4	610	38		

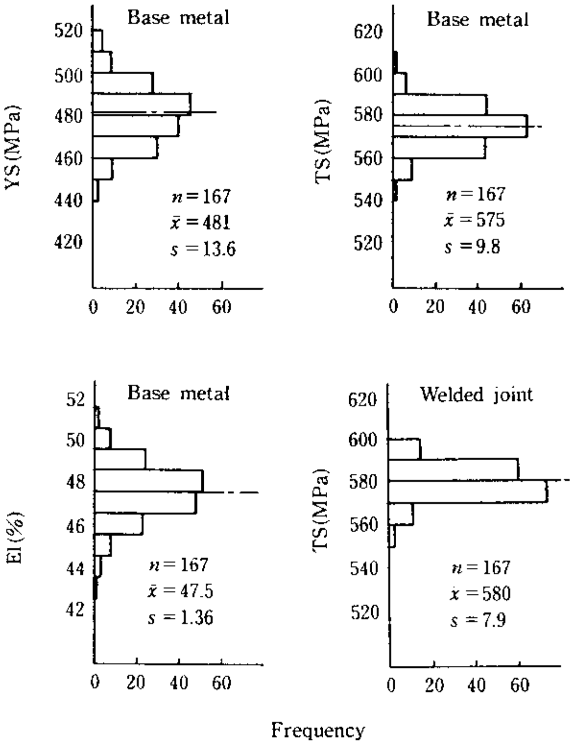


Fig. 15 Transverse tensile test results ($t = 22.2$ mm) on the UO pipes

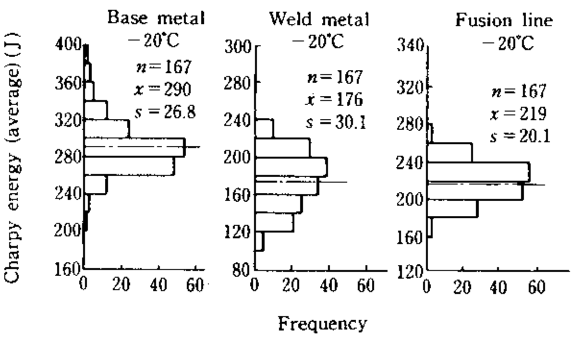


Fig. 16 Charpy impact test results (2 mm V, 10 × 10) on the UO pipes

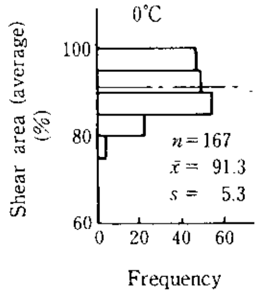


Fig. 17 DWTT results on the UO pipe

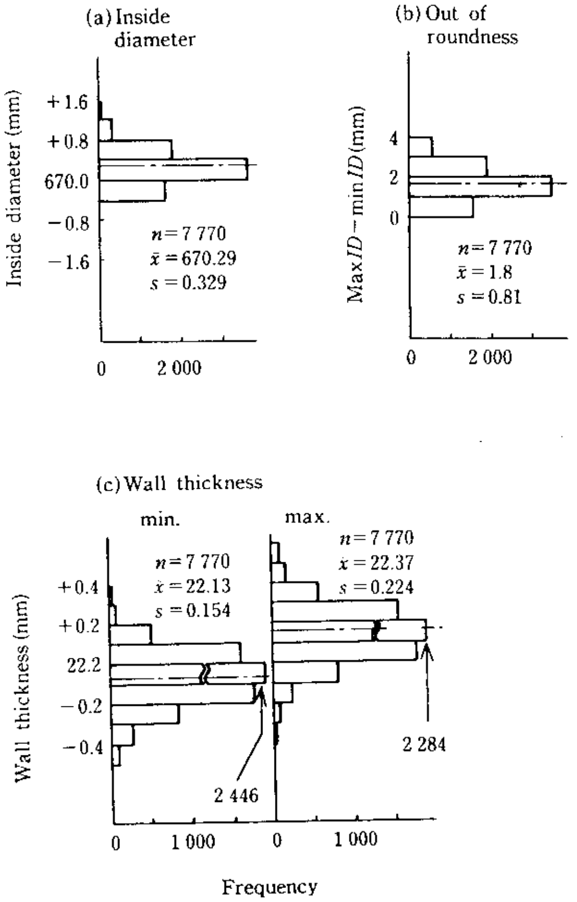


Fig. 18 Dimensional measurement results of the UO pipes (end-A)

in length. Results of dimentional measurements are shown in **Fig. 18.** Dimensional accuracies, such as out of roundness, were almost equal to those of pipe made of conventional CR(controlled rolled) plates, thus demonstrating the homogeneity of the mechanical properties of each plate. Moreover, no cracks whatsoever were detected in the HIC test conducted under the conditions specified in NACE standard TM-02-84.

5 Conclusions

Kawasaki Steel produced about 50 000 t of submarine line pipe for oil transportation in the North Sea area, with the following results:

(1) By applying MACS, Kawasaki Steel's controlled rolling and accelerated cooling process, API 5L-X60 steel plates with P_{CM} of 0.150% or less were stably produced in plate thicknesses of 22.2 and 23.8 mm. Furthermore, mechanical properties after pipe-making fully satisfied the required specifications.

(2) Because the P_{CM} of this steel plate was held to low values and newly developed welding wire and flux were used for submerged arc welding, it was possible to ensure HV = 248 or less as the hardness of the girth welds, with relatively low heat input applied.

(3) Because the Mn content was set to low levels and the P and S contents were controlled to the ultralow levels of 80 ppm or less and 15 ppm or less, respectively, no cracking occurred, as ascertained in the HIC test after pipe-making.

(4) With plate 38.1 mm in thickness for use as buckle arresters, results completely satisfying property requirements were obtained by the addition of Mo, even with a low P_{CM} level of 0.180%.

The above results demonstrate that low-P_{CM}, extra-thick API 5L-X60 steel plate can be produced stably and in a large quantity by use of the controlled rolling and accelerated cooling process.

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