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Manufacturing of New 26-inch ERW High-Test Line Pipe*

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Factors contributing to the improved product quality of the new mill have been examined and the following results have been obtained:

(1) The application of vertical-bending type caster with shielding is effective in reducing weld defects.
(2) Controlled rolling techniques have made it possible to yield better mechanical properties and toughness of the hot strip.
(3) Pipe-making technique by cage roll forming, heat input control in welding, fully automatic control in seam annealing and full-body ultrasonic testing have contributed to the production of ERW pipes with higher quality and reliability.
(4) Supplementary mechanical properties such as yield strength drop due to Bauschinger effect, yield and burst strength by internal pressure, and tensile strength at lower temperatures have been quantitatively determined.

1 Introduction

Needless to say, the largest field where line pipes are demanded is petroleum and natural gas transportation. The line pipes for petroleum and natural gas transportation are divided according to usage into those for gathering (OD 4–24 in.), for trunk line or transmission line (OD 16–56 in.) and for distributing line (OD 2–16 in.)[1]. Although ERW pipes, submerged arc weld pipes and seamless pipes have conventionally been used for these purposes, the percentage of ERW pipes has recently increased along with a further promotion of quality assurance system for welds.

In order to cope with this situation, Kawasaki Steel began manufacturing 20 in. ERW pipes (OD $6^5/_8$–20 in.) in 1964 prior to other manufacturers, and furthermore commenced operation of the 26 in. ERW mill from October, 1978, in order to meet the recent trend toward increased dimensions and tensile strength of line pipes. This mill, capable of manufacturing products having maximum outside diameter of 26 in. (660.4 mm) and maximum wall thickness of 0.63 in. (16.0 mm), is one of the largest in the world.

In this paper, the authors will describe the outline how the quality of the line pipes produced by this mill has been improved and guaranteed, regarding quality improvement in hot coils, quality control in the pipe manufacturing process, quality assurance system and some examples of quality results. In addition, the authors will report the results of detailed examination on the characteristics of mechanical strength.

2 API Standards and Customer's Supplementary Standards

2.1 ERW High-Test Line Pipe with Large Outside Diameter

The principal chemical composition of API 5LX, classified according to grades, is shown in **Table 1**, and the tensile requirements in **Table 2**. Elements such as Nb, V, Ti etc. are used to increase strength by

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* Rearranged from following two articles: (1) *Kawasaki Steel Giho*, **13** (1981) 1, pp. 53–62, (2) *ibid.*, pp. 63–79
** Chita Works
*** Mizushima Works
**** Research Laboratories

Table 1 API requirements for heat analysis (Twenty- second edition) (wt%)

Grade	C[1] max.	Mn[1] max.	P max.	S max.	Nb min.	V min.	Ti	Check frequency
X42	0.28	1.25	0.04	0.05	—	—	—	If required, each heat
X46, X52	0.30	1.35	0.04	0.05	—	—	—	
X56[2], X60[2]	0.26	1.40	0.04	0.05	0.005[3]	0.02[3]	0.03[3]	
X65[4]	0.26	1.60	0.04	0.05	0.005[5]	0.02[5]	—	
X70[2]	0.23[6]	1.60[6]	0.04	0.05	—	—	—	

1) For grades X65 and below, for each reduction of 0.01 per cent below the specified maximum carbon content, an increase of 0.05 per cent manganese above the specified maximum is permissible, up to a maximum of 1.45 per cent.
2) Other chemical analyses may be furnished by agreement between purchaser and manufacturer.
3) Either Nb, V, Ti or a combination thereof, shall be used at the discretion of the manufacturer.
4) For grades X65 shown in size 16 in. and larger with wall thickness 0.500 in. and less, the chemical composition shall be as shown on as agreed upon between the purchaser and manufacturer. For other sizes and wall thickness the chemical composition shall be as agreed upon between the purchaser and manufacturer.
5) Either Nb or V or a combination of both shall be used at the discretion of the manufacturer.
6) For each reduction of 0.01 per cent below the specified maximum cabon contnet, an increase of 0.05 per cent manganese above the specified maximum is permissible.

Table 2 Tensile requirements

(Twenty-second Edition, API)

Grade	Yield strength (psi) min.	Tensile strength (psi) min.	Elongation (GL=2") % min.	Weld-tensile strength[4] (psi) min.	Test frequency
X42	42 000	60 000	See foot note[3]	60 000	For pipe 4½ in. O.D. and smaller; one per each lot of 450 lengths or less
X46	46 000	63 000		63 000	
X52	52 000	66 000[1]		66 000[1]	
		72 000[2]		72 000[2]	For pipe ⅝ in O.D. through 12¾ in. O.D.; one per each lot of 200 lengths or less
X56	56 000	71 000[1]		71 000[1]	
		75 000[2]		75 000[2]	
X60	60 000	75 000		75 000	
X65	65 000	77 000[1]		77 000[1]	For pipe 14 in. O.D. and larger; one per each lot of 100 lengths or less
		80 000[2]		80 000[2]	
X70	70 000	82 000		82 000	

1))For pipe less than 20 in. O.D. with any wall thickness, and for pipe 20 in. O.D. and larger with wall thickness grater than 0.375 in.
2) For pipe 20 in. O.D. and larger with wall thickness 0.375 in. and less
3) The minimum elongation in 2 in. shall be determined by the following formula:

$e = 625\,000 \frac{A^{0.2}}{U^{0.9}}$ e = minimum elongation in 2 in. per cent rounded to nearest 1.2 per cent.
A = cross sectional area of the tensile test specimen in square in the based on specified outside diameter or nominal specimen width and specified wall thickness, rounded to the nearest 0.01 sq. in or 0.75 sq. in whichever is smaller
U = specified tensile strength, psi

4) For pipe 8⅝ in. O.D. and larger with any wall thickness

precipitation hardening and fine granulation after the addition of trace elements in the composition of the grades above X56[2].

Moreover, the supplementary requirements for toughness, as shown in **Table 3**, are applied in the scope of the grades above X52 and outside diameters above 20 in. (above 508.00 mm) and when designated by customers.

2.2 Dimensional Accuracy of ERW Line Pipe with Large Outside Diameter

The main requirements for the specifications of

Table 3 Charpy impact testing[1] and drop weight tear testing[1]

(Twenty-second Edition, API)

Test item	Method	Test temperature	Test frequency	Requirement
Charpy V-notch test (two-thirds size)	According to ASTM A 370	32°F or 50°F	Three transverse specimens per each heat	Average shear value; min. 35% All heat averaeg shear value; min. 50%
DWTT	According to API RP 5L3	32°F or 50°F	Two transverse specimens per each heat	At least 80 per cent of the heats shall exhibit a fracture appearance shear area of 40 per cent or more

1) For welded pipe 20 in. O.D. and larger, grade X52 and higher, if required

Table 4 Tolerances on dimensions and weights, workmanship (Twenty-second edition, API)

Item		Requirements		
Tolerances on dimensions	Outside diameter	Pipe body	Less than 20 in Larger than 20 in	±0.75% ±1.00%
		Pipe ends for a distance of 4 in from the end of the pipe	10¾ in and smaller 12¾ in to 20 in 20 in and larger	+1/16 in, −1/64 in +3/32 in, −1/32 in +3/32 in, −1/32 in
	Out of roundness	Pipe ends	Larger than 20 in	±1%
	Wall thickness		18 in O.D. and smaller 20 in O.D. and larger	+15.0%, −12.5% +19.5%, −8.0%
Tolerances on weights		Single lengths	Regular weight series Special light weight series	+10.0%, −3.5% +10.0%, −5.0%
		Carload lots A carload is consider to be a minimum of 40 000 lb		−1.75%
Workmanship	Dents	Depth : Max. 1.4 in Length : Max. 1.2×O.D.		
	Offset of plate edges	Max. 0.060 in		
	Height of inside weld bead	Max. 0.060 in		
	Trim of inside weld bead	Wall thickness 0.151 in to 0.301 in 0.301 in and larger	Depth of trim max. 0.015 in max. 0.05 t	
	Defects	Laminations at bevel face : max. 1.4 in (transverse dimension)		

API 5LX as to the tolerance of dimensions, external appearance and workmanship are shown in **Table 4**. Tolerance of dimensions is provided for two groups of outside diameters not less than 20 in. and less than 20 in. This is because the pipes with outside diameters not less than 20 in. have hitherto consisted of submerged arc weld pipes rather than ERW pipes. All the pipes produced by the 26 in. ERW mill meet the requirements for pipes with outside diameters less than 20 in.

3 Manufacture of 26-inch ERW Line Pipe

3.1 Characteristics Required of Hot Strip Material

3.1.1 Internal quality

Hot coil of high cleanliness with little nonmetallic inclusions and impure elements is required for securing the quality of ERW pipe welds and obtaining good ultrasonic flaw detection test results.

3.1.2 Mechanical properties

The API Standard specifies chemical composition and mechanical properties for high strength pipes, as described above. Therefore, components as well as rolling conditions should be designed so that these requirements are met. On the other hand, there is a phenomenon in which the Y.S. of steel pipes falls below the Y.S. of hot strip due to Bauschinger Effect[3], and the decrement (ΔY.S.) differs according to t/D (wall thickness/outside diameter), as shown in **Fig. 1**. Therefore, the material of the hot strip as hot coil must be designed to a strength level taking this Y.S. into consideration. On the other hand, toughness is not specified in particular but depends upon the specifications agreed with customers, though recently line pipes used under unfavorable conditions such as a cold region are increasing and excellent low temperature toughness is often required. In this case, however, specifications required of hot strip are generally severer than those for steel pipes since toughness develops a tendency to deteriorate due to the cold working in the pipe manufacturing process.

3.1.3 Stability of formability in pipe making

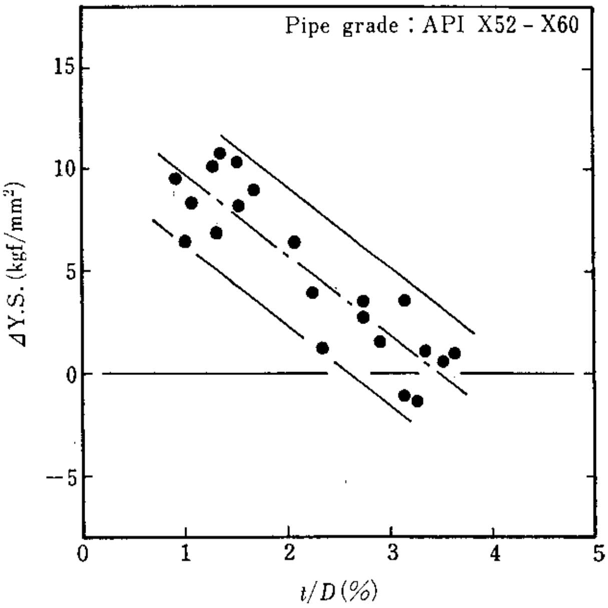
The formability in pipe making has a great influence upon the quality of ERW pipe welds. Unstable formability causes such troubles as follows, resulting in a remarkable deterioration in strength and toughness of welds.

(1) Increase of UT failure due to defective bead cutting.
(2) Seam annealer follow-up failure due to seam torsion.
(3) Bilateral unevenness in the metal flow of ERW pipe welds and so on.

This tendency becomes more pronounced as the diameter becomes larger and the wall thickness becomes smaller. Accordingly, it is necessary in the stage of hot strip to sufficiently control the flatness, gage accuracy, hot coil appearance, etc. which seem to affect the formability.

3.2 Steelmaking Technique

It is necessary for securing the weld quality of the high strength ERW line pipe to decrease not only nonmetallic inclusions but also impure elements. Although the techniques for this purpose have been developed individually as a steelmaking technique, an attempt has been made to improve the internal quality by applying these techniques to the hot coil for line pipe. The outstanding features of these techniques are as follows.



t : Wall thickness
D : Outside diameter
ΔY.S. : Difference between Y.S. of hot strip and that of pipe in transverse direction

Fig. 1 Relation between t/D and ΔY.S. of high strength line pipe

3.2.1 Protection from oxidation

Most of the secondary oxidation in the continuous casting process is due to the oxidation between ladle and tundish. As a technique to prevent this oxidation, application of a long submerged nozzle between ladle and tundish, as shown in **Fig. 2**, was developed. The effect of the application of a long submerged nozzle is shown in **Fig. 3**. In this figure, the comparison of the decrement of total oxygen content from the end of ladle refining of low-carbon aluminum killed steel up to tundish by the application of a long submerged nozzle with that by the conventional sealing with Ar gas is illustrated. It is clear from this figure that the application of a long submerged nozzle brings about a larger decrement of total oxygen content as well as a more marked effect of oxidation protection.

3.2.2 Vertical bending type continuous caster

The vertical bending type continuous caster is

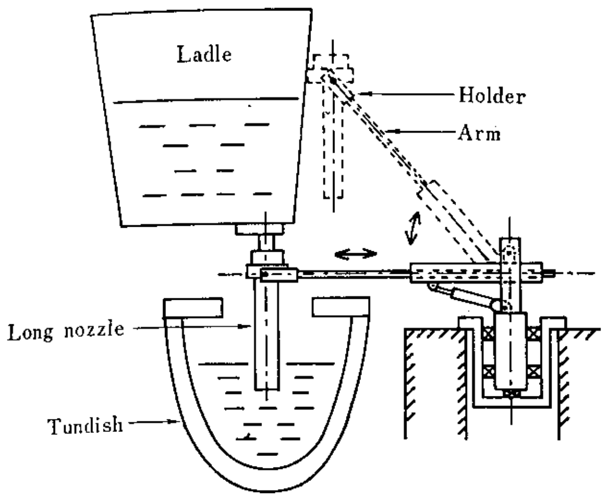


Fig. 2 Schematic diagram of long nozzle sealing method

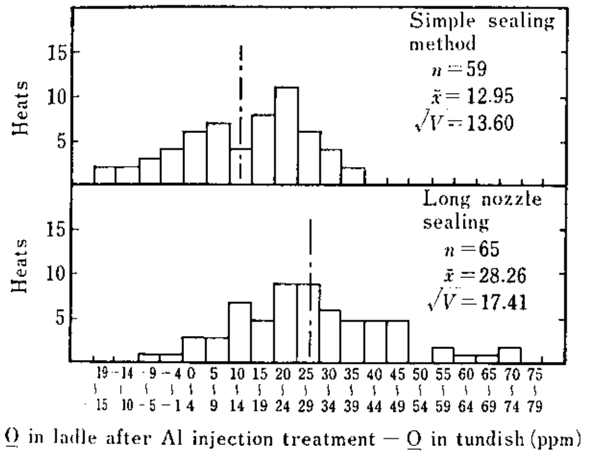


Fig. 3 Distribution of oxygen content in melt sealed with long nozzle and without long nozzle

advantageous for decrease of large inclusions, compared with the bow or circular type continuous casting machine. The results of investigations into the inclusions larger than 100 μm in diameter in the width direction of 50 kgf/mm^2 grade slabs are shown in Fig. 4[4]. In the case of the vertical bending type continuous caster, the large inclusions decreased to $^1/_{10}$–$^1/_{20}$ there is little difference among them in the cast slab width direction, and they are nearly uniformly distributed. In the cast slab thickness direction, on the other hand, no accumulation zone of nonmetallic inclusions[5] such as that seen in the case of the bow or circular type continuous caster occurs, as shown in Fig. 5, and thus the advantage of the vertical bending type caster is clearly evident from this fact.

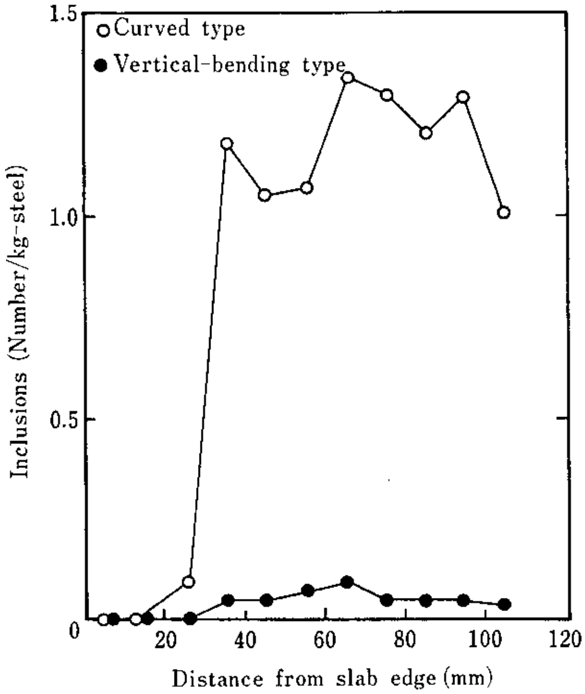


Fig. 4 Large inclusions ($\geq$ 100 μm) distribution in transverse direction of continuously cast 50 kgf/mm^2 grade slab

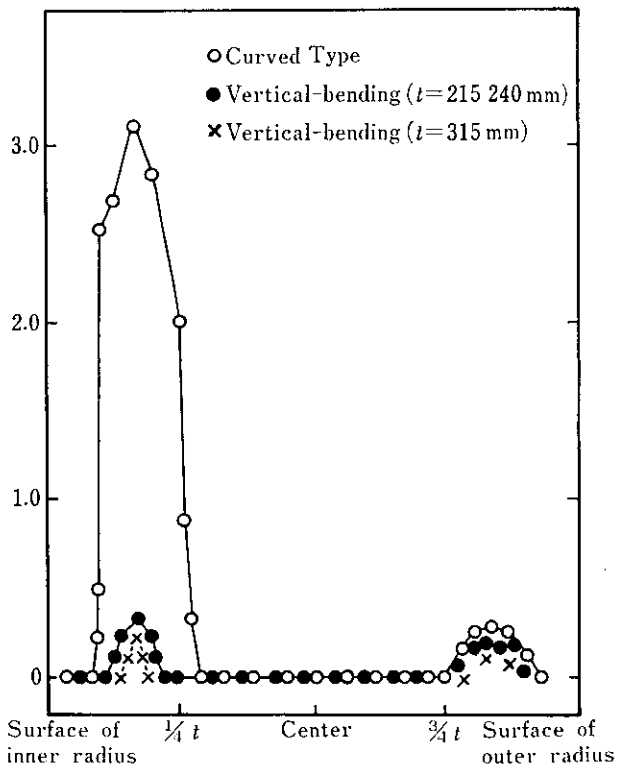


Fig. 5 Large inclusions ($\geq$ 100 μm) distribution in through-thickness direction of continuously cast 50 kgf/mm^2 grade slab

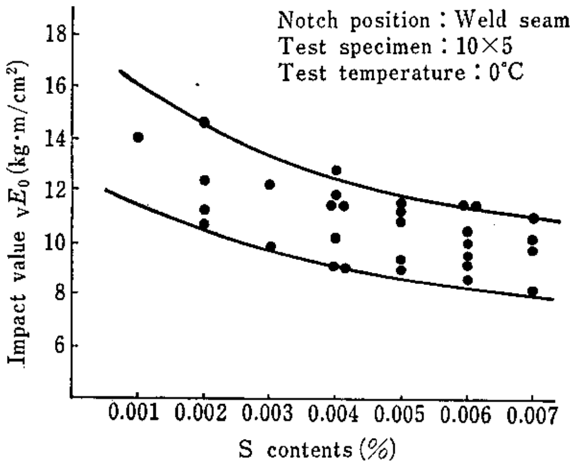


Fig. 6 Effect of S contents on impact values of weld position

3.2.3 Reduction of impure elements

The reduction technique for impure elements has made great progress. Above all, the development of desulfurization technique is so outstanding that the mass-production of ultra-low sulphur steel has been made possible. As an example of this, the Charpy impact values of the weld for the S content in grade X60 are shown in **Fig. 6**. It is clear that the impact properties of the weld are improved step by step by sharply reducing the S content.

3.3 Hot Rolling Techniques

3.3.1 Improvement of mechanical properties

For manufacturing the hot strip provided with both high strength and toughness at low temperature in the Nb-V series, it is necessary to obtain fine ferrite-pearlite structure. For this reason, various conditions from slab reheating to hot coiling are severely controlled by the controlled rolling techniques[6,7], including the model predicting mechanical properties[8], developed by Kawasaki Steel. This is effective also for securing the uniformity of the material and structure of hot strip in the longitudinal direction.

Major factors affecting mechanical properties are described below, with their effects compared to the actual data obtained through the manufacturing process.

(1) Slab reheating temperature
The slab reheating temperature has great influence upon the dissolved rate of Nb (C, N) and the austenite grain size at the time of slab reheating. If the reheating temperature is lowered as far as possible in the range within which the precipitated

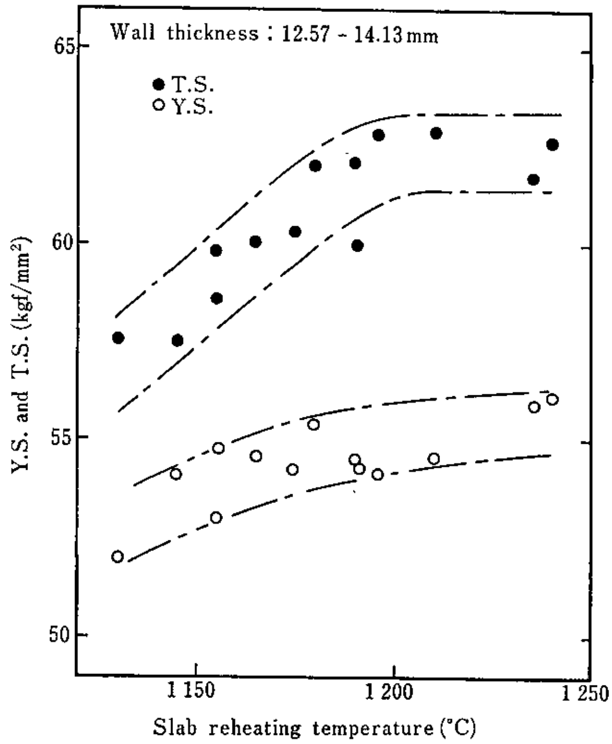
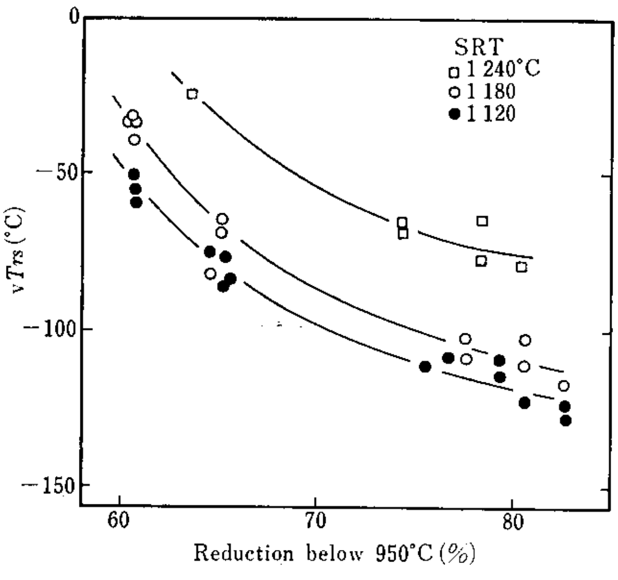


Fig. 7 Effect of slab reheating temperature on Y.S. and T.S. of control-rolled high strength hot strip



$_vTrs$: Charpy 2mm V-notch transition temperature
SRT : Slab reheating temperature

Fig. 8 Effect of reduction below 950°C and SRT on $_vTrs$ of control-rolled high strength hot strip

Nb (C, N) is completely dissolved, the austenite grains at the time of reheating can be made finer and the toughness can be improved even more. Low C material is advantageous since the temperature required for the solution of Nb (C, N) can be lower than in the case of high C material. The influence of reheating temperature upon tensile properties and impact properties is shown in **Figs. 7** and **8**. As the reheating temperature lowers, the tensile strength lowers, too, while the yield strength does not change markedly. This is probably because, in the case of low temperature heating, the amount of Nb (C, N) precipitate in the austenite zone which does not contribute to the strength increases according to the difference of the dissolved Nb content while the yield strength can be secured by the effect of grain refining. It is clear, in addition, that low temperature reheating is superior in respect of the transition temperature. This is probably because the toughness deterioration due to the effect of grain refining and precipitation hardening is reduced.

(2) Reduction ratio

For ferrite grain refining, it is important to apply great rolling reduction in the stage of rough rolling of the recrystallized region of austenite and to carry out finish rolling at the uncrystallized region of austenite (below 950°C) to increase the rolling reduction, thereby introducing many deformation bands into the grain and increasing the transformation sites of ferrite, and above all, the effect of the latter is remarkable[6,9]. The influence of the reduction ratio of the unrecrystallized region of austenite upon the impact properties and tensile properties is shown in **Figs. 8** and **9**. It is clear from these figures that if the reduction ratio is increased, grain refining will be promoted and the transition temperature will be greatly improved.

Besides, though Y.S. and T.S. rise with the increase in reduction ratio, the yield ratio (Y.S./T.S.) develops a tendency to rise since the rising rate of Y.S. is greater than that of T.S.; so care should be taken in deciding the reduction ratio in the case where upper limit restriction is set up for the yield ratio. **Photo. 1** shows the relationship between the reduction ratio and the crystalline structure. It is clear from this photograph that crystal grains are refined as the reduction ratio increases.

(3) Finish rolling delivery temperature

Fig. 10 shows the relationship between the finish rolling delivery temperature and the tensile properties. If the finish rolling delivery temperature

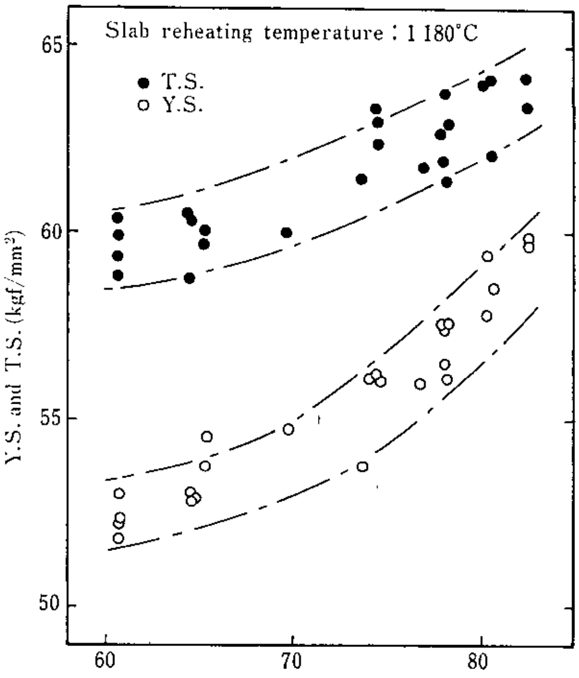


Fig. 9 Effect of reduction below 950°C on Y.S. and T.S. of control-rolled high strength hot strip

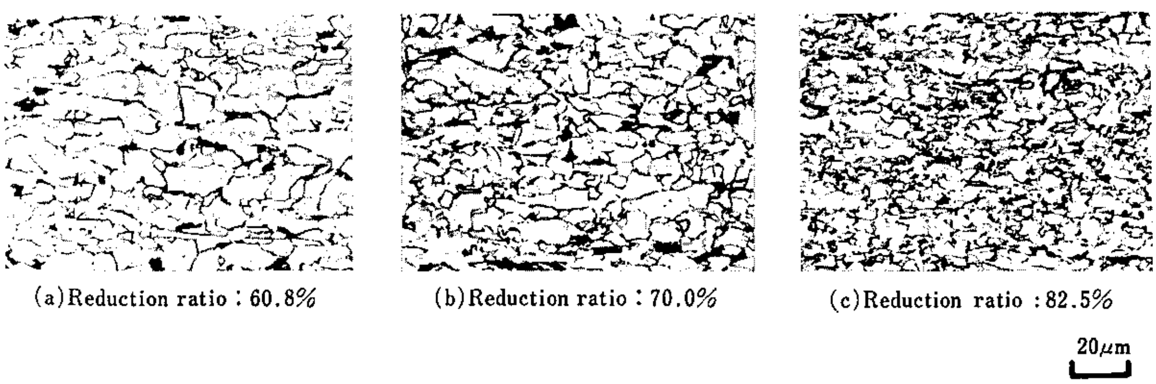


Photo. 1 Effect of reduction ratio below 950°C on the microstructure

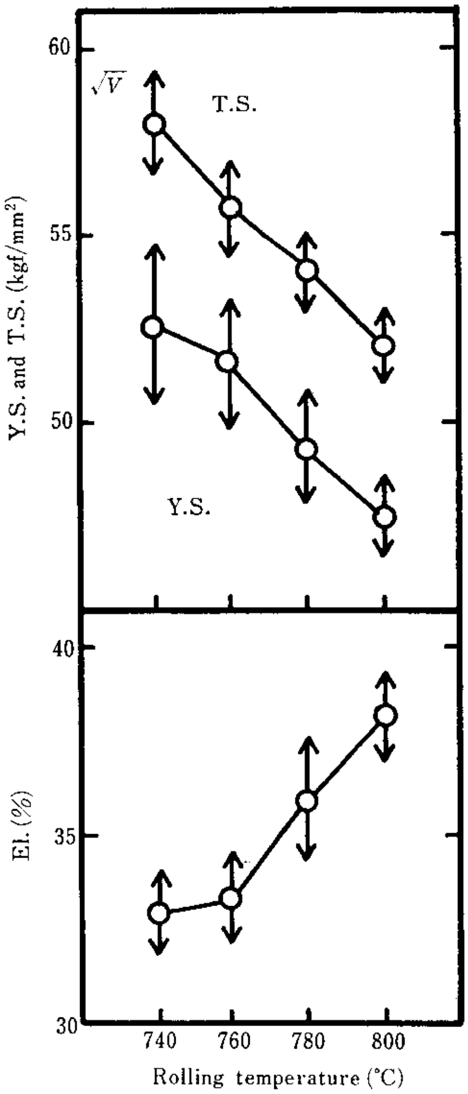


Fig. 10 Effect of rolling temperature on the mechanical properties

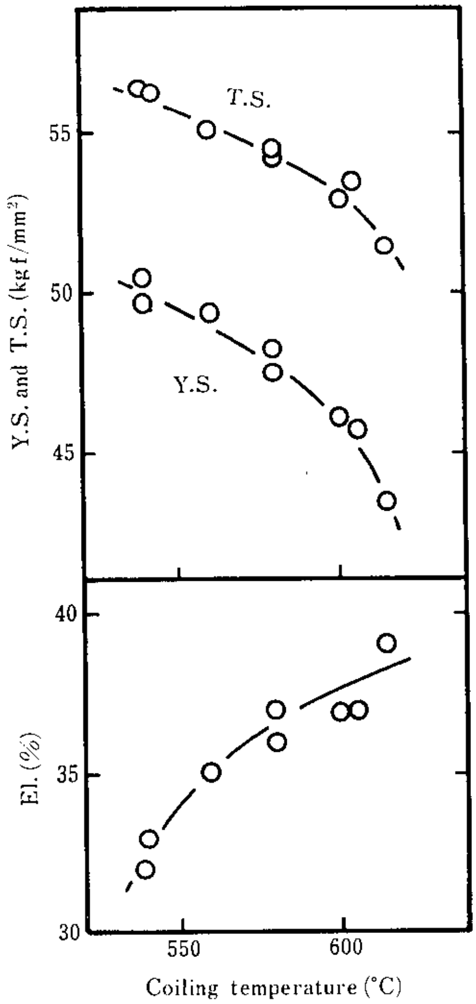


Fig. 11 Effect of coiling temperature on the mechanical properties

rises, the strength will lower, assumedly because the density of the deformation bands introduced during finish rolling is reduced so that the crystalline grain diameter increases. In addition to this, since the impact properties generally tend to deteriorate, it is inadvisable to raise the finish rolling delivery temperature, but in actuality, a proper temperature is chosen in consideration of the shape and easy passing-through of the plate. Besides, since toughness would be deteriorated in transformation range rolling[10], the finish rolling delivery temperature should be set so as not to go below the point of Ar_3 transformation, but care should be taken since the phenomenon that the point of Ar_3 transformation rises due to strain induced transformation will take place if the rolling reduction ratio increases[11].

(4) Coiling temperature

The relationship between the coiling temperature and the tensile properties is shown in **Fig. 11**. If the coiling temperature is low, ferrite grains will be refined, fine Nb (C, N) and V(C, N) will be precipitated into ferrite, and the strength will increase, since the cooling rate will be increased. If the coiling temperature is too high, undesirable phenomena such as coarse grains and reduced strength would be likely to follow, whereas if it is too low, telescoping of hot coils would be likely to increase, exercising bad influence upon the formability in the pipe-making process. Therefore, in manufacturing hot coils, a proper coiling temperature was fixed, and the mechanical properties were adjusted by other factors.

The factors that exert an influence upon the mechanical properties, as well as their effects have been described above. Thus, in carrying out material design, it is necessary to study properties requirement and combine each condition so that the optimum material may be obtained.

3.3.2 Control for stable formability

The properties required of hot strip as described in the preceding section 3.1.3 are in detail the following: (1) Camber; (2) Gage accuracy; (3) Profile; and (4) Flatness. These requirements are met in the hot strip mill, as follows:

(1) Camber
The telescoping length in the state of a hot coil corresponds well to the amount of camber in a rewound hot strip, as shown in **Fig. 12**. Thus, good control of hot coiling is important for camber prevention. Generally speaking, it is more difficult to obtain hot coil of good appearance for high-strength, large-width material, but good appearance of hot coil is secured by ensuring correct tension in coiling, and proper gap between pinch roll and wrapper roll and by setting up an adequate pressure of the wrapper roll cylinder as well as by making use of a bending roll before the pinch roll as shown in **Fig. 13**. This is because restraining force acts against the force in the cross direction of hot coil, thereby restraining telescoping since a large contact area can be obtained through support of a hot strip at three points by the upper and lower pinch rolls and the bending roll, as shown in **Fig. 14**(b), compared with the support at two points by the upper and lower pinch rolls, as shown in **Fig. 14**(a).

(2) Gage accuracy
The requirements are met by improving the setup accuracy of the process computer and the A.G.C. (Automatic Gage Control) accuracy.
Moreover, keyless bearing[12] in the back-up rolls

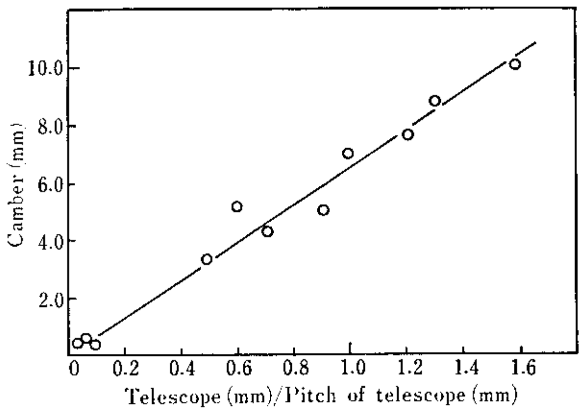


Fig. 12 Relation between camber of strip and telescope of hot coil

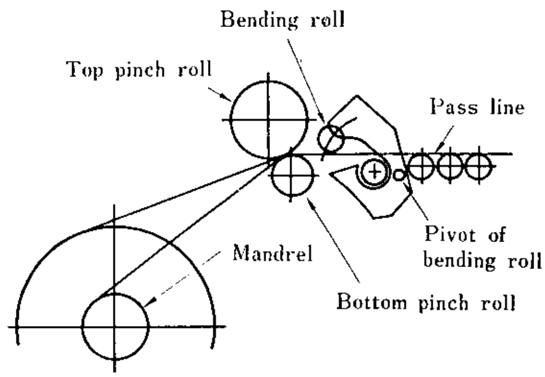


Fig. 13 Schematic diagram of down coiler with a bending roll

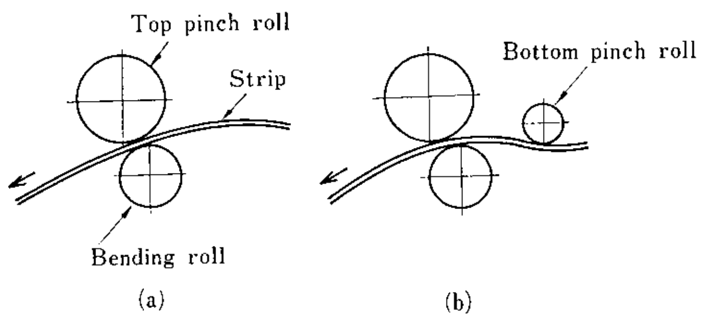


Fig. 14 Behavior of strip (a) without and (b) with a bending roll

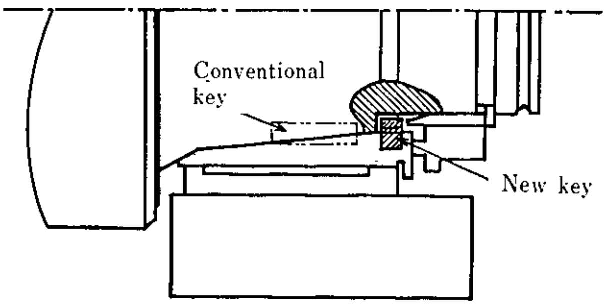


Fig. 15 Schema of key-less bearing

of finishing stand as shown in **Fig. 15**, is applied for further effect.

(3) Profile
The profile of hot strips in the width direction has to have a proper crown symmetric to the width center so that the weld seam may not meander at the time of pipe forming.
For this purpose, a profile meter is installed at the rear of the hot finishing mill for the on-line detection of profile, thereby feeding back necessary draft adjustment or change at roughing and finishing stands so as to obtain proper profile.

(4) Flatness
No edge wave is essential for the shape of the hot strip for ERW pipe. In order to meet this requirement, a hydro-sensor[13] as shown in **Fig. 16** is installed on the rear surface of the finish-rolling mill, and on the basis of the information of flatness obtained from this hydro-sensor, flatness control[14] for the feedback to the roll bending pressure at the final stand and to the rolling reduction distribution of F1–7 stands is carried out, and thus good flatness is obtained.

3.4 Pipe-Making Technique

The main equipment and their specifications for the manufacture of line pipes at our 26 in. ERW pipe mill are shown in **Table 5**, and the available size range in **Fig. 17**: t/D (wall thickness/outside diameter) up to a minimum of 0.96 % is possible. A typical example of the manufacturing process of high-test line pipes is shown in **Fig. 18**. The heat input control in welding, the quality control equipment of the weld zone and the pipe-making technique by cage forming, which are important above all from a qualitative point of view and characteristic to this mill, are described below.

3.4.1 Welding condition control

(1) Stabilized forming
For stabilization of the quality of weld zone, it is necessary first of all that the coil edge at the time of welding be stabilized without local deformation and strain. Since full-cage roll forming[15] and downhill curve, as shown in **Fig. 19**, are employed at this mill, no sudden deformation occurs at the time of forming, with gradual and uniform plastic deformation obtained, and local concentrative deformation as well as distortion at the coil edge greatly reduced. Therefore, this mill is advantageous for forming steel pipes with large outside diameter and thin wall thickness, and since the rigidity of the cage stand is sufficiently high for steel pipes with large wall thickness as well, stabilized forming is possible up to a wall thickness of 16.0 mm.

(2) Welding heat input control
The behavior and weldability of the forming equipment upon which the quality of weld zone depends were controlled visually by the operator in the past, so that they were likely to be affected

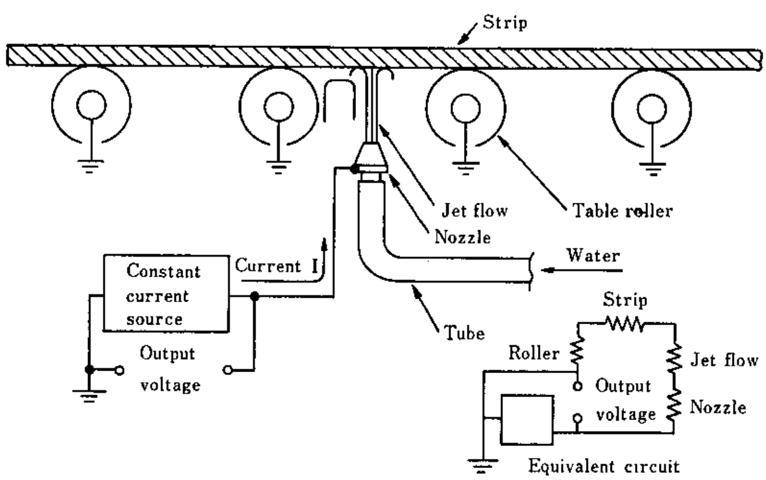


Fig. 16 Principle of flatness measurement and its equipment circuit

Table 5 Main equipment and their specifications of cage forming type ERW mill

Forming	Full-cage roll forming type Break down : 4 std. DC 150 kW×1, 45 kW×3 Fin pass : 3 std. DC 185 kW×3
Welder	Thermatool VT-600 400 kHz
Seam annealer	400 kW×4, 1 000Hz
Sizing	Sizer : 4 std. DC 185 kW×3
Finishing equipment	Pipe end cut-off machine×2, Pipe middle cut-off machine×1, Facer×2 Anti-rust coating machine×1,
Inspection equipment	Skelp-edge UST, Flattening tester Hydrostatic tester, Seam UST, Full body UST Weighing machine, Marking machine

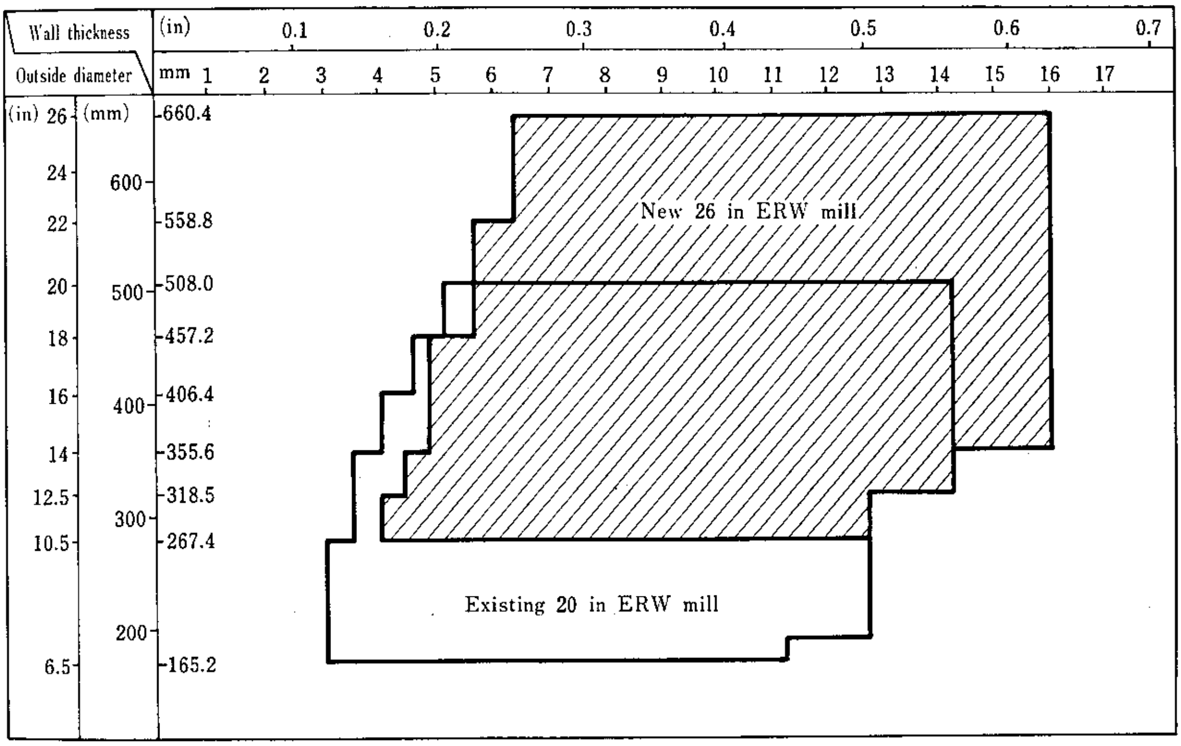


Fig. 17 Available size range

by operator's individuality and difference in the degree of skill. As for high-test line pipe, in particular, it was extremely difficult to obtain stabilized conditions since the tolerance of proper conditions is small. At our mill, therefore, weld portions are constantly controlled by the use of a highspeed camera photographs, as shown in **Fig. 20**, which are compared with normal welding conditions so that optimum welding conditions may be obtained. The normal welding conditions are shown in **Photo. 2**(a). In addition, the welding heat input is controlled at high accuracy based on the information on the temperature measured by a thermometer installed immediately after welding so that the quality of weld portions has been remarkably stabilized. These conditions are shown in **Fig. 21**.

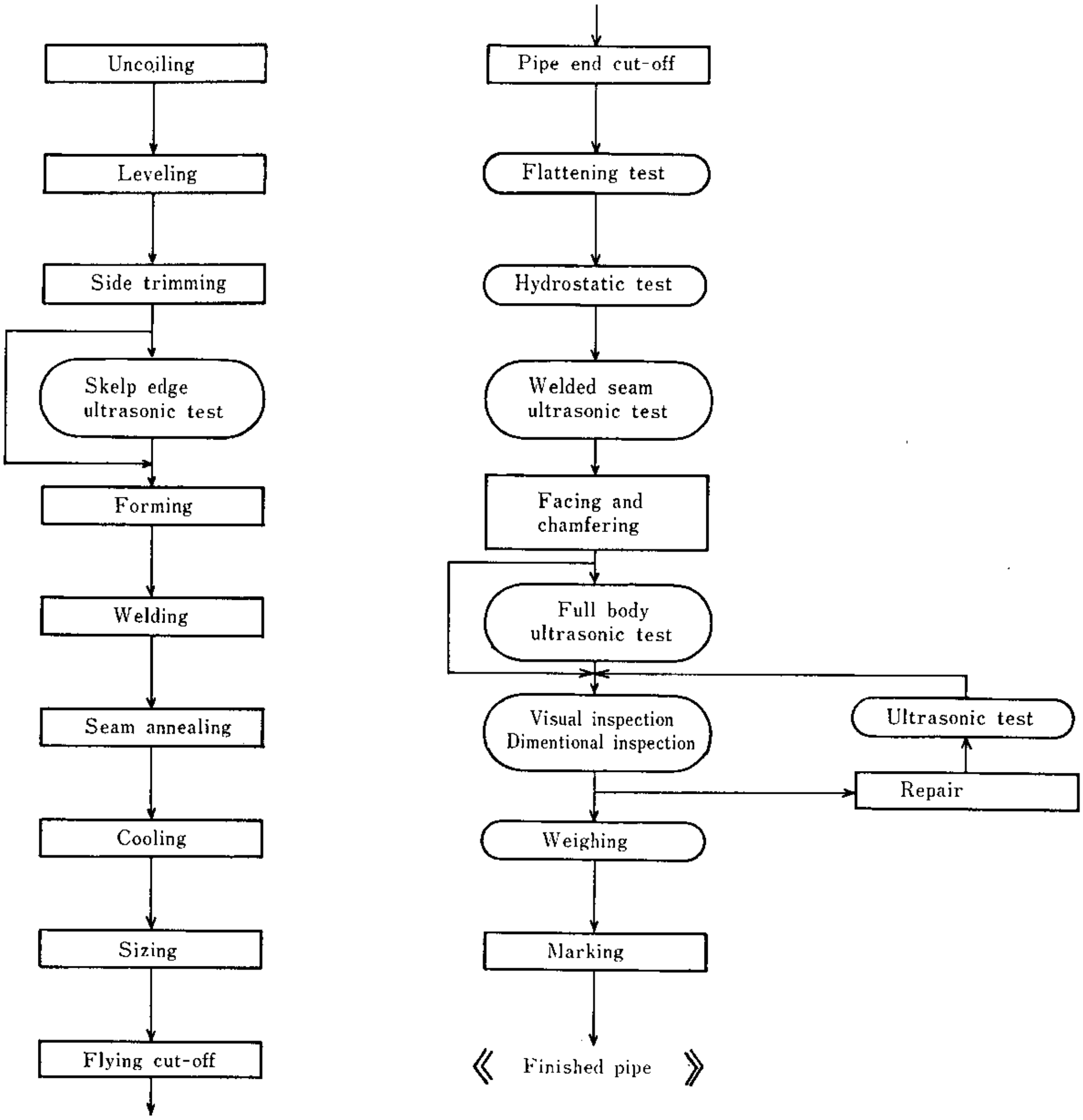


Fig. 18 Manufacturing and inspection processes of the line pipe

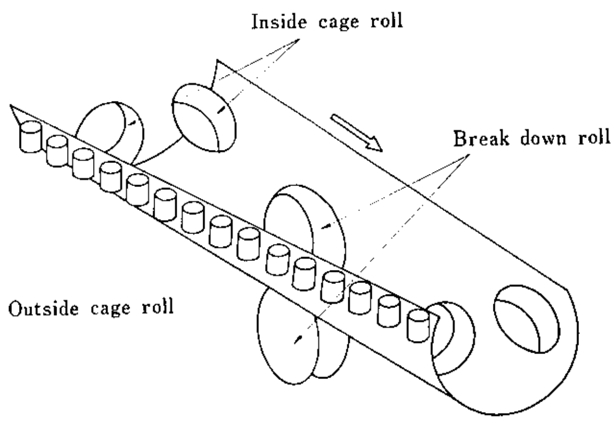


Fig. 19 Full cage roll forming

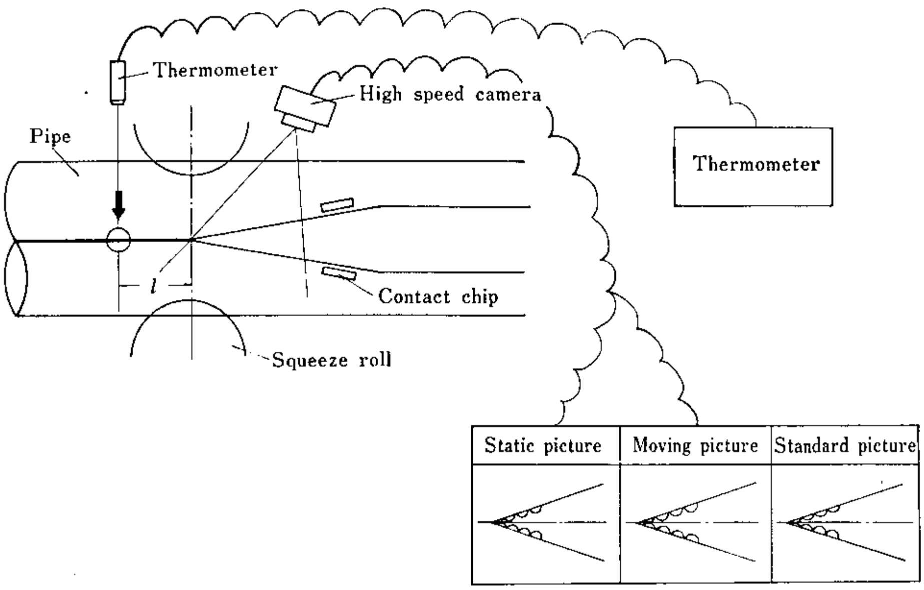


Fig. 20 Schematic diagram of heat input control for welding

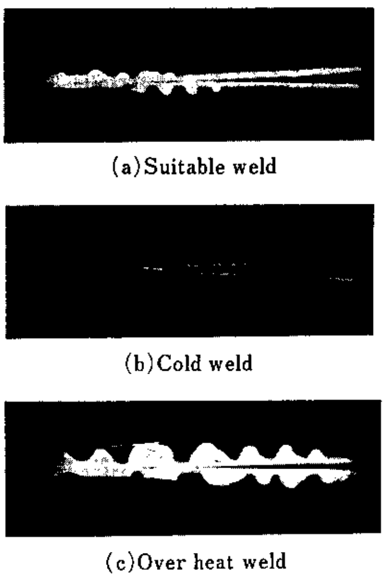


Photo. 2 Dependence of Vee-shape appearances on welding heat input

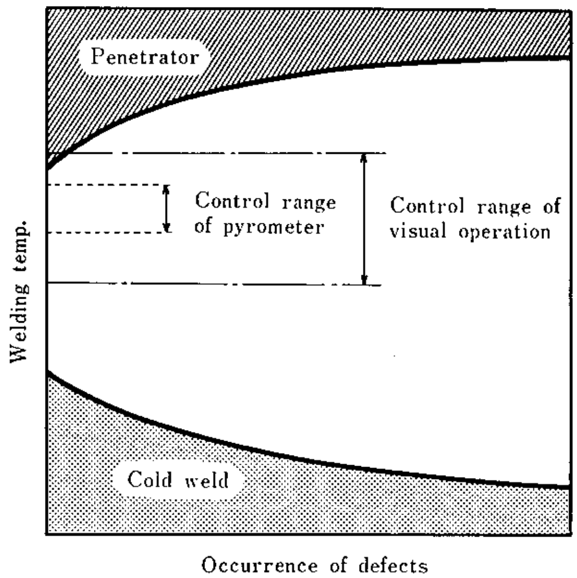


Fig. 21 Control range of welding temperature

3.4.2 Quality assurance system equipment

(1) Spark detector

The sparking phenomenon which occurs at the time of welding gives rise to serious trouble from the standpoint of welding quality since it causes local cold welds. Therefore, an electrostatic marking machine was developed and installed at our mill. It detects the sparking phenomenon as soon as it occurs, notifies it to the operator and, at the same time, marks the position of spark occurrence on the pipe.

This spark detector detects abnormal plate current when sparks occur. The outline of this spark detector is shown in **Fig. 22**. By the introduction of this equipment, the quality assurance system for weld zone has further progressed.

(2) Fully-automatic control seam annealer[15]

Although the heat treatment of welded seam zone is carried out by the induction heating method in

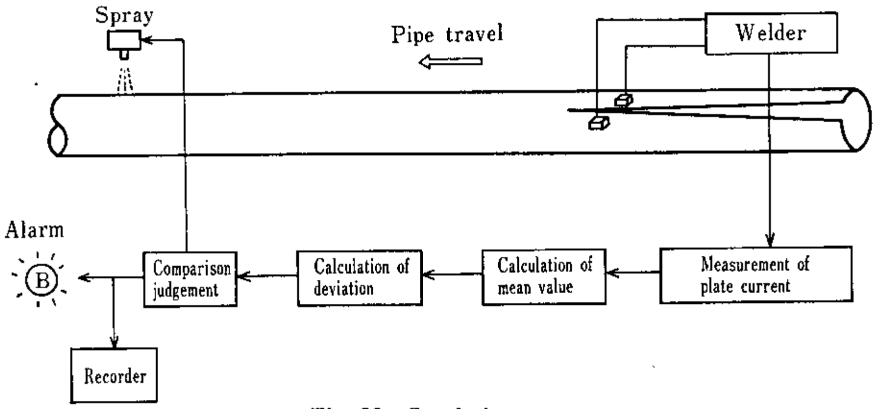


Fig. 22 Spark detector

order to bring about an improvement in the toughness of weld zone, uniformity of hardness, etc., there is a trend toward the severer control of products with the higher quality of products. In order to cope with these situations, an automatic control system such as automatic heat control, automatic weld-seam tracer, etc. is incorporated in this equipment.

(3) NDI (Nondestructive Inspection) equipment[16]
In order to make assurance doubly sure in the quality assurance system, our mill is equipped with a full-body ultrasonic flaw detector in addition to an ultrasonic flaw detector for coil edges and an ultrasonic flaw detector for welds (with six probes). In this full-body ultrasonic flaw detector, a plural number of probes built in four heads are rotated at high speed in the circumferential direction of a traversing pipe, so that every defect existing can be detected not only on both inner and outer surfaces of the pipe in the longitudinal and circumferential directions but also within the material.

4 Quality Results

Examples of the quality results of high-test line pipes with small wall thickness API 5LX X60 (660.4 mmϕ × 6.35 mm$t$; $t/D = 0.96\%$) which were recently produced at the 26 in. ERW Pipe Mill are shown in **Figs. 23–27** and **Photos. 3** and **4**. Every hot coil is made of fully-killed continuous casting steel of Al-Si in the low C- and Mn-Nb-V components, and the hot coils whose strength and toughness are increased by controlled rolling at the hot strip mill are used. It is clear from the ladle analysis in **Fig. 23** that it is high cleanliness steel of which every chemical component is well controlled and of which impure elements such as P, S, etc. are reduced as far as possible in order to cope with welding defects such as hook crack defects, nonmetallic inclusions, etc. in the upsetting portions of the weld and to improve the toughness.

From the tensile properties and Charpy impact properties shown in **Fig. 24** and from the DWTT transition temperature in **Fig. 26**, it is clear that every pipe has excellent strength and toughness.

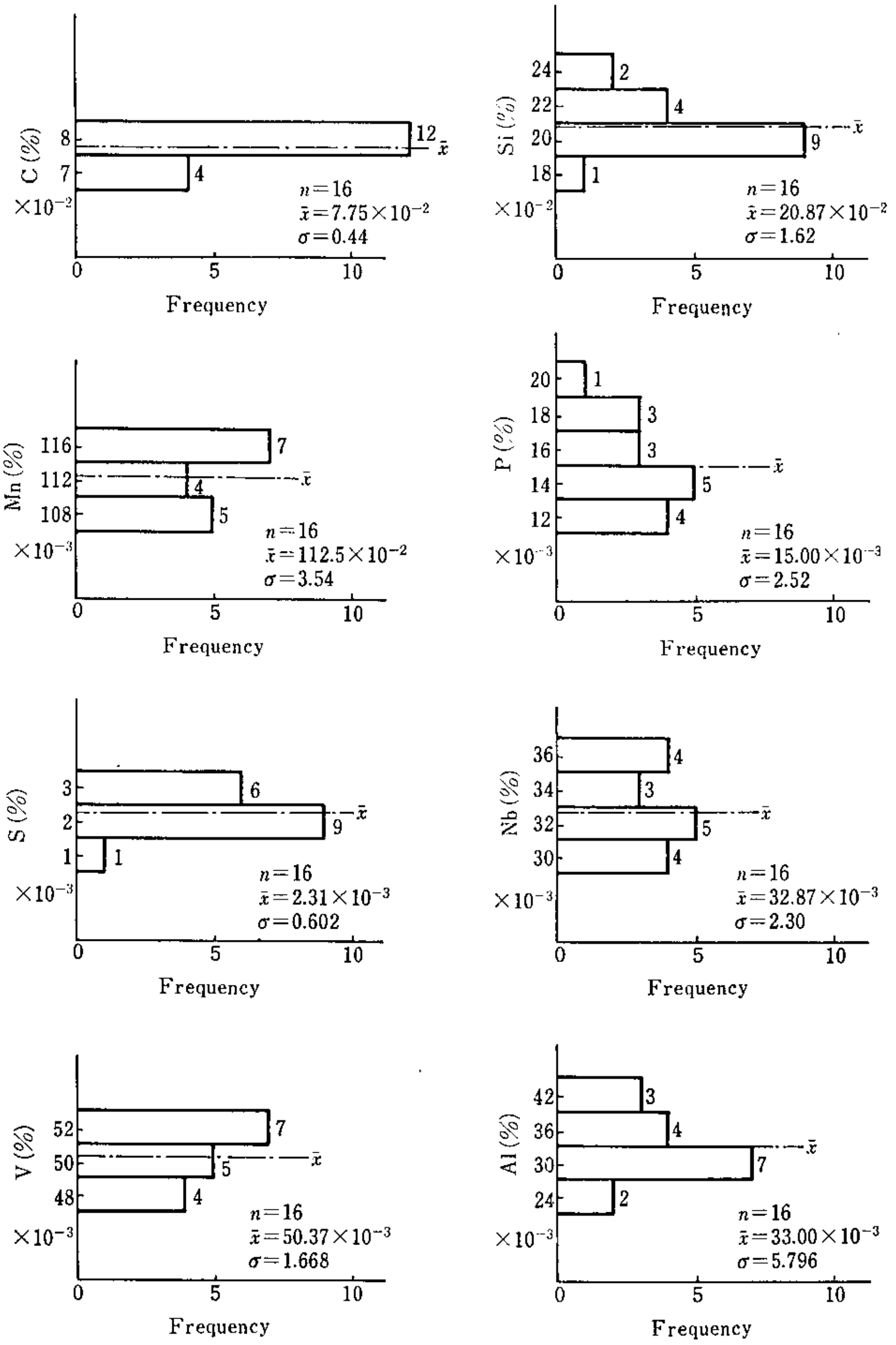
From the hardness distribution shown in **Fig. 27** and additionally from the macro- and micro-graphs in **Photos. 3** and **4**, no remarkable changes are observed in the weld zone comparing with other base metal. It is clear from the results of dimensional measurement shown in **Fig. 25** that even the line pipe with large outside diameter of 26 in. meets the API specifications for line pipe with outside diameter of less than 20 in. and thus is a pipe of high gage accuracy.

In addition, an example of the results of burst test by internal pressure at room temperature is shown in **Table 6** and **Photo. 5**. The burst position is always observed in the base metal, and the base metal breaking stress meets the API specifications for base metal tensile strength.

5 Mechanical Strength Properties of 26-inch ERW Pipe

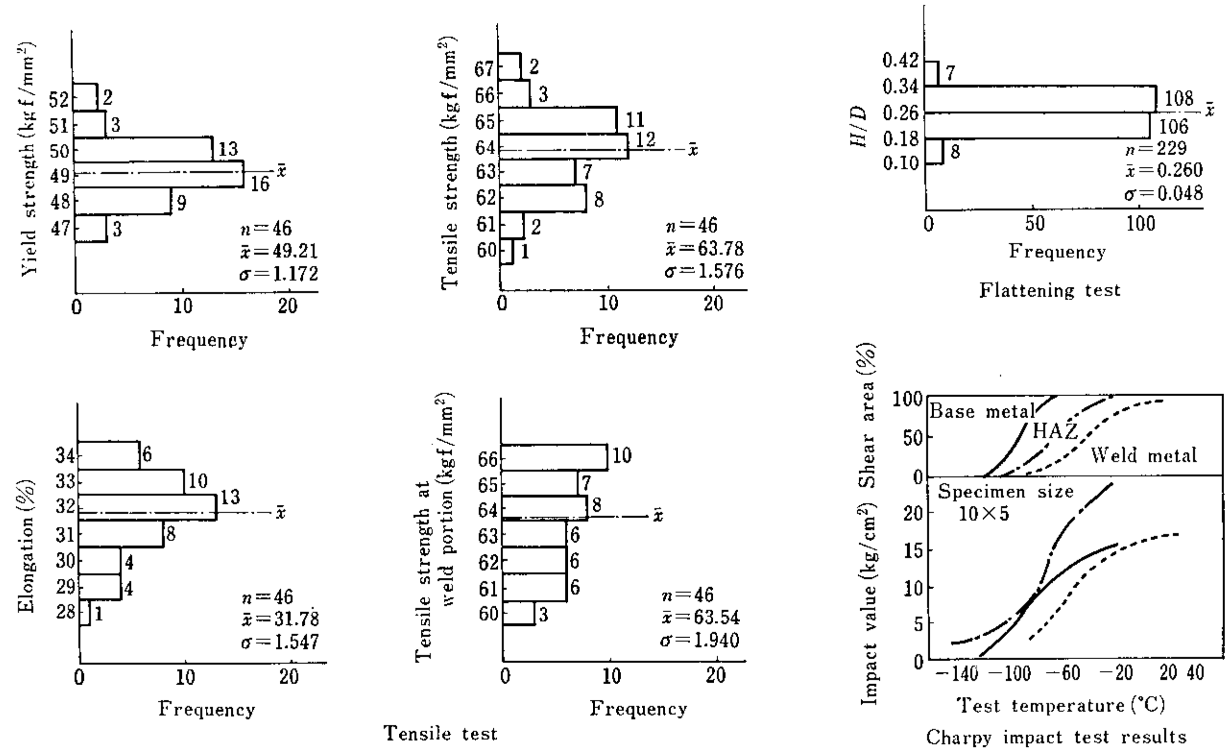
Normally, the mechanical properties according to the standards for line pipes are often provided by the Charpy impact test as well as by the tension test at room temperature for the flattened sheet specimen, and the results on quality have been described above.

However, these values alone are not sufficient to argue the adaptability under the actual working environmental conditions. A variety of studies have been reported accordingly, on the subjects of full-body burst test[17–19], ductile fracture at lower temperature[20,21], fatigue characteristics[21,22], Bauschiger effect[23–25], etc. Now, with this in mind, in order to clarify supplementary mechanical properties of the 26 in. ERW pipe which has been newly put in use, the



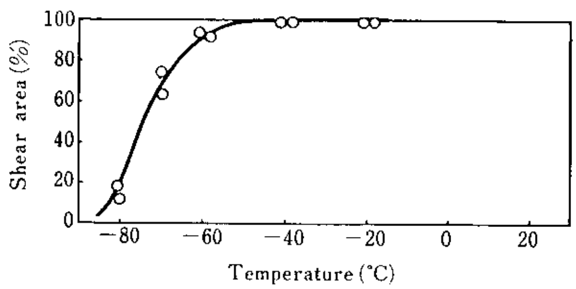
Sample : API 5LX X60 : 660.4 mmϕ × 6.35 mm$t$

Fig. 23 Chemical composition (Ladle analyses)



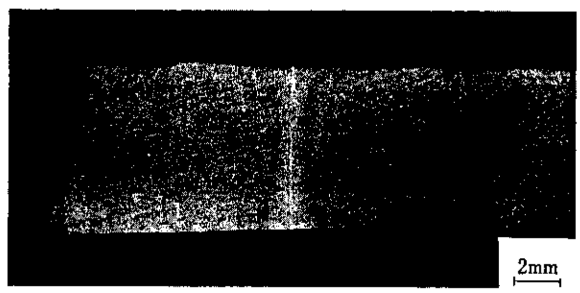
Sample : API 5LX X60 : 660.4 mmϕ×6.35 mm$t$

Fig. 24 Mechanical properties



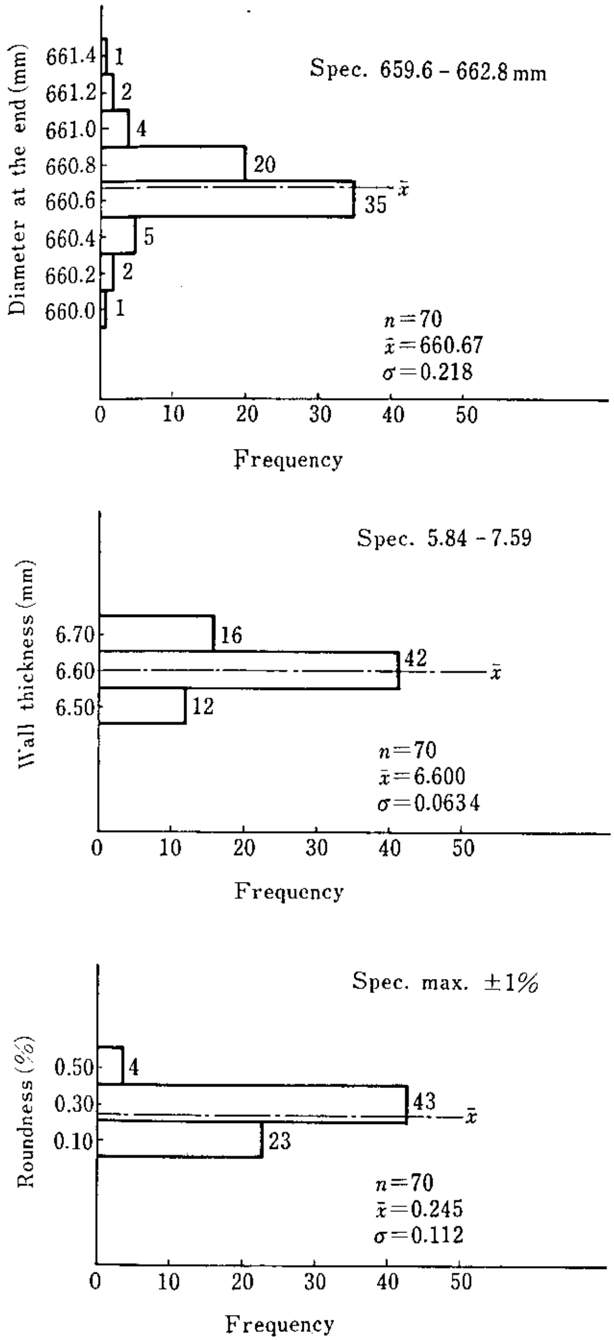
Sample : API 5LX X60 : 660.4 mmϕ×6.35 mm$t$

Fig. 26 DWTT transition curves in transverse direction



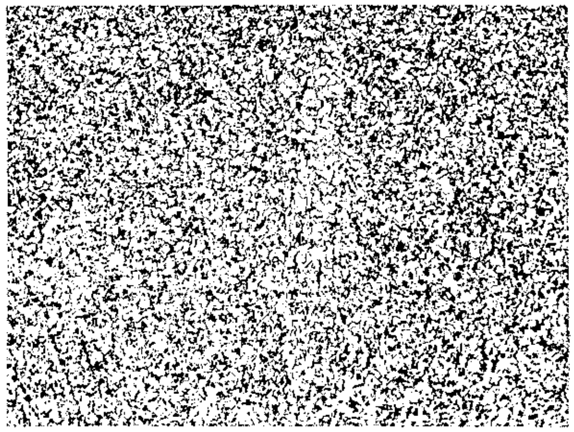
Sample : API 5LX X60 660.4 mmϕ×6.35 mm$t$

Photo. 3 Optical macrograph at weld zone

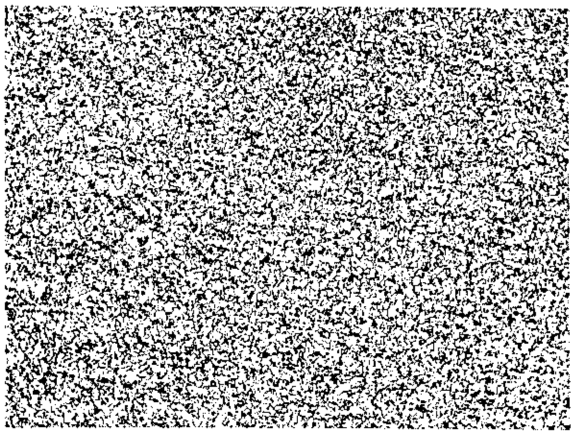


Sample : API 5LX X60 : 660.4 mmϕ×6.35 mm$t$

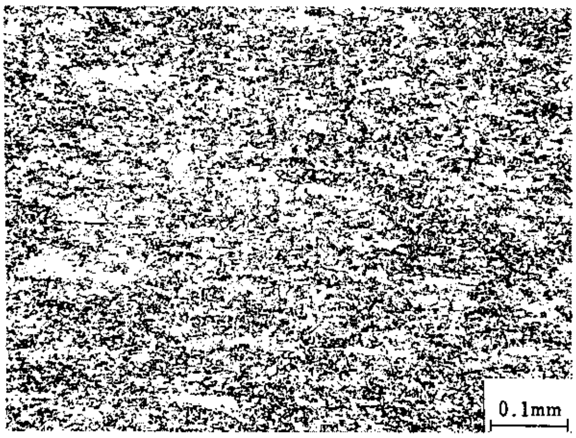
Fig. 25 Variation of outside diameter, wall thickness and outside roundness



Welded seam

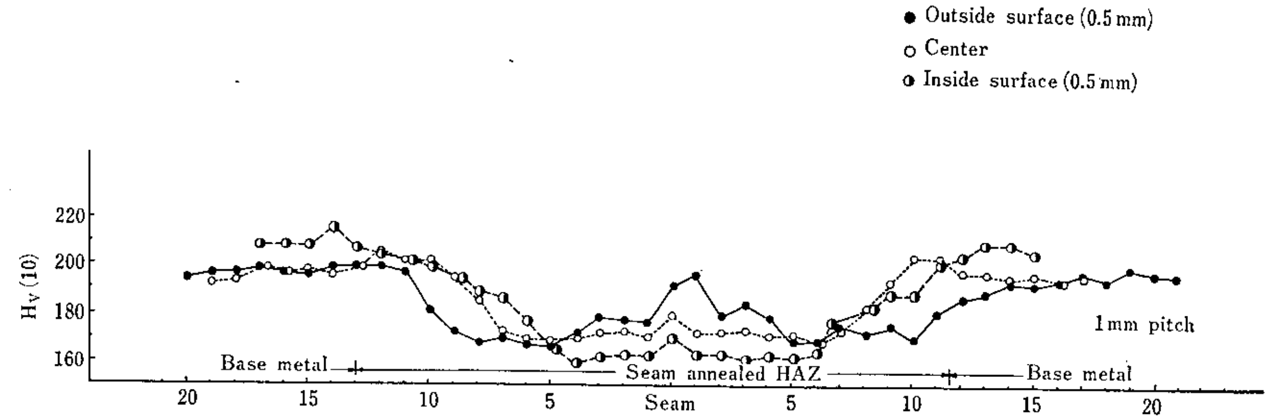


HAZ
(2 mm portion from welded seam)



Base metal
(180 degree from welded seam)
Sample : API 5LX X60 660.4 mmϕ×6.35 mm$t$

Photo. 4 Optical macrograph at weld zone



Distance from weld seam (mm)

Sample : API 5LX X60 : 660.4 mmϕ×6.35 mm$t$

Fig. 27 Hardness distribution in transverse direction

Table 6 Burst test results

Grade	Size	Burst test results			Strap tensile properties		
		Pressure at rupture (kgf/mm^2)	Stress at rupture (kgf/mm^2)	Burst position	Y.S. (kgf/mm^2)	T.S. (kgf/mm^2)	El. (%)
X60	26"×0.250"×6 m	124	64.5	Base metal	49.8	64.1	31.0
X65	16"×0.562"×6 m	431	61.4	Base metal	51.3	60.4	35.1

Stress at rupture $= P \cdot D/200\ t$

P = Pressure at rupture

D = Outside diameter

t = Wall thickness

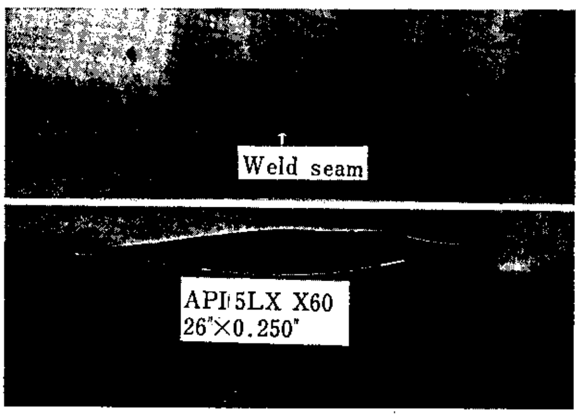


Photo. 5 Appearance of the pipe after burst test

experimental results of the Bauschinger effect, the yield and burst strength by internal pressure, tensile strength at lower temperatures, etc. will be described in the following as to the specimen having the strength and chemical components shown in **Table 7**.

The relationship between the variation of yield strength ΔY.S. (= pipe Y.S. − coil Y.S.) before and after the pipe-making process and the coil strength before the pipe-making process of 26 in. ERW pipes of various pipe dimensions and grades is shown in **Fig. 28**. The higher the coil Y.S. of hot coils is, the more the reduction of yield strength ΔY.S. after pipe-making process, being considerably affected by the Bauschinger effect.

Table 7 Chemical composition of hot rolled sheet tested

Pipe size	Pipe grade	Chemical composition (wt%)							
		C	Si	Mn	P	S	Al	Nb	V
24"ϕ×15.88 mm$t$	X42	0.21	0.16	0.81	0.017	0.011	0.020	—	—
20"ϕ×14.27 mm$t$	X60	0.18	0.20	1.29	0.020	0.009	0.003	0.041	0.026
24"ϕ× 6.35 mm$t$	X60	0.17	0.18	1.17	0.016	0.004	0.025	0.039	0.010
24"ϕ×12.7 mm$t$	X65	0.08	0.21	1.33	0.016	0.002	0.027	0.038	0.031

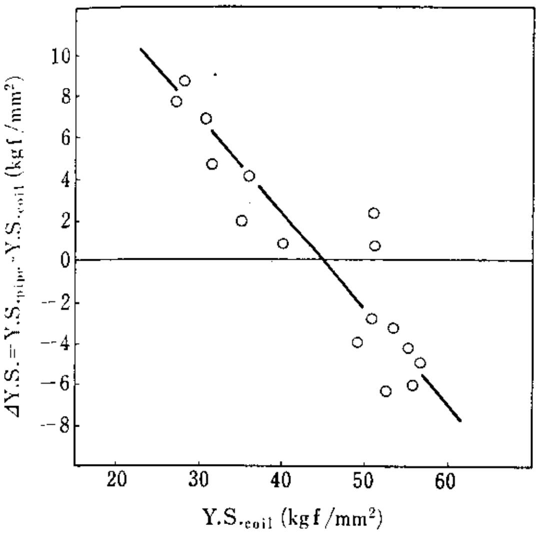


Fig. 28 Relation between ΔY.S. and Y.S. of coil materials in transverse direction

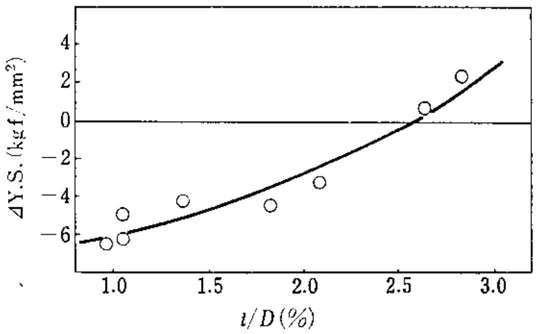


Fig. 29 Relation between Y.S. and t/D for X60–65 grade pipes

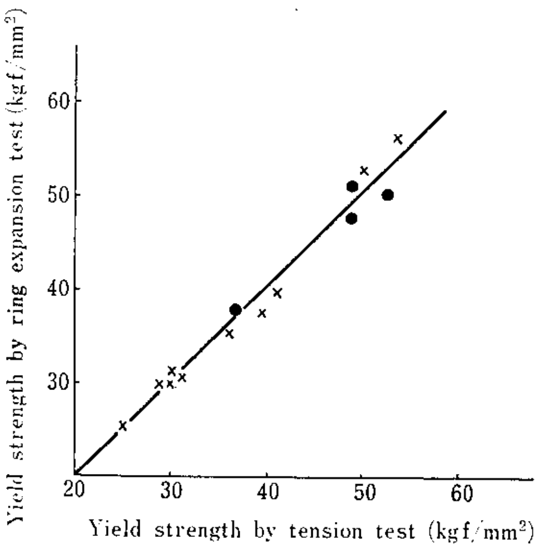


Fig. 30 Relation between yield strengths by ring expansion test and by tension test

The relationship between Y.S. and t/D (wall thickness/outside diameter) in the API 5LX X60–65, and 26 in. ERW pipes of high strength is shown in **Fig. 29**. The Bauschinger effect is affected not only by the coil strength of hot coils but also by pipe dimensions, and the less t/D is, the more the Y.S. reduction after the pipe-making process.

The comparison of yield strength by internal pressure measured by the ring expansion test with Y.S. measured by the flattened sheet tension test (both sampled before the on-line hydrostatic test) is shown in **Fig. 30**. It is clear from this figure that, when an expanding process is provided as in the case of the UOE pipe, the ring expansion test Y.S. is higher than the flattened sheet tension test Y.S. due to the influence of tensile pre-strain[26,27], while both have nearly equal values in the case of the 26 in. ERW pipe.

The comparison of the yield strength by internal pressure measured by the burst hydrostatic test with the one by the ring expansion test is shown in **Fig. 31**. While the pipe is closed at both ends with domed end plates and internal pressure is exerted also in the axial direction of pipe in the case of the burst hydrostatic test, it is opened to both ends and no stress is exerted in the axial direction of pipe in the case of the ring expansion test; the yielding conditions of these tests differ from each other. As is clear from the figure, Y.S. by the burst hydrostatic test gives a value larger by approximately 15% than that by the ring expansion test Y.S. and it nearly agrees with the theoretical value obtained from Von Mieses' yielding condition's equation[24].

The relationship between the fracture strength by burst hydrostatic test and the tensile strength is shown in **Fig. 32**. The value of the fracture strength by burst

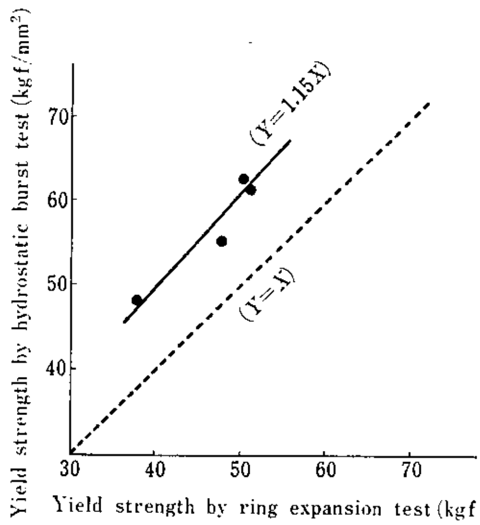


Fig. 31 Relation between yield strengths by hydrostatic burst test and by ring expansion test

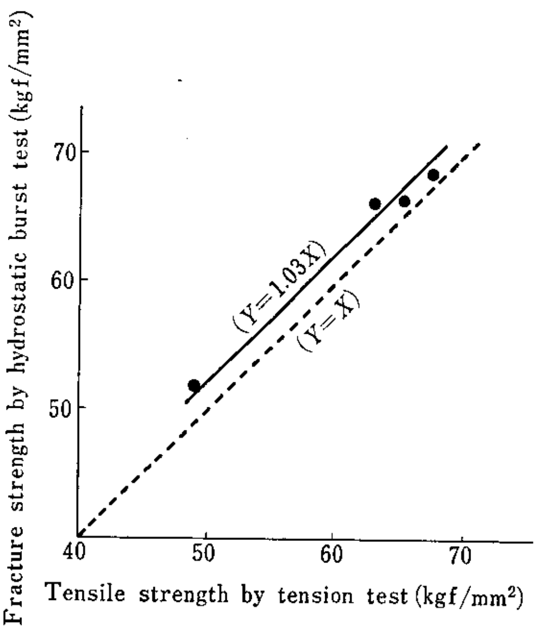


Fig. 32 Relation between fracture strength by hydrostatic burst test and tensile strength by tension test

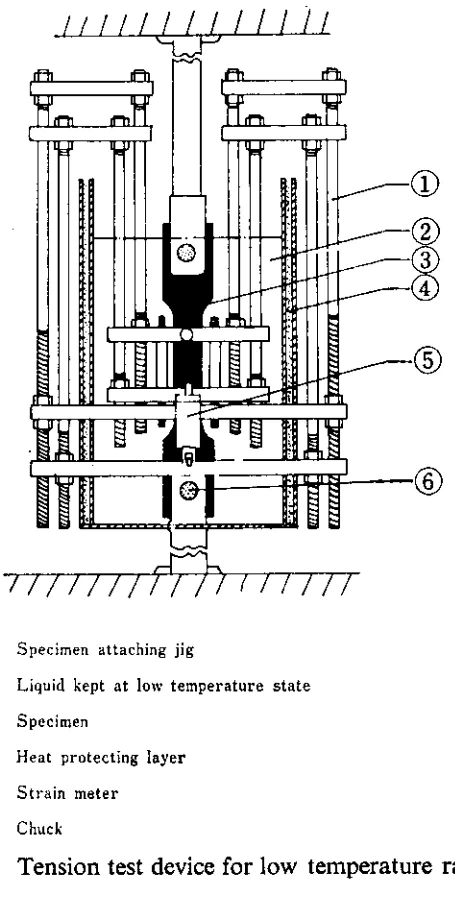


Fig. 33 Tension test device for low temperature range

hydrostatic test is somewhat larger than that of the tensile strength, and this nearly agrees with the experimental equation:

$$Y = 1.034X$$

which was obtained by Hasebe et al[19].

The outline of the tension test device for low temperature range is shown in **Fig. 33**. Tension test specimens of 60 mm length and 10 mm width in reduced section were prepared from a weld zone and from a base metal portion, and tension tests at lower temperature were carried out in the temperature range from room temperature to −120°C. An example of the test results (for API 5LX X65, 609.6 mmϕ × 12.7 mm$t$) is shown in **Fig. 34**. As is clear from the figure, both Y.S. and T.S. gradually increased with lowering of the temperature, and the following relationship was recognized between strength σ and temperature T (K).

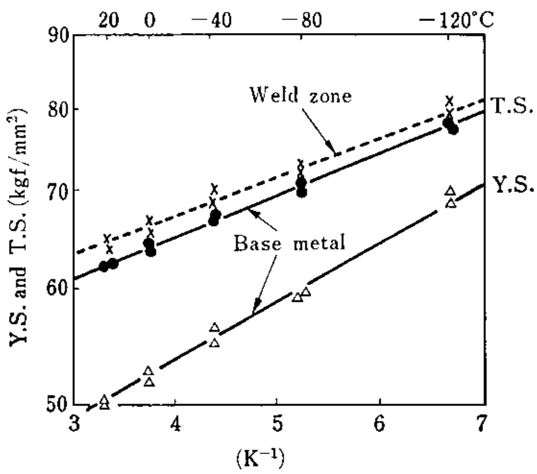
$$\sigma = A_{\exp}(B/T) \cdots\cdots\cdots\cdots\cdots\cdots \textbf{(1)}$$

(A, B: constants)

In addition to this, the strength of the weld zone proved to be higher than the base metal strength in the low temperature zone similarly as in the case measured at room temperature. Now, when the strength at room temperature (20°C) is represented by σ_{20}, eq. **(1)** can be rewritten as follows:

$$\sigma = \sigma_{20\exp}\{B(1/T - 1/293)\} \cdots\cdots\cdots \textbf{(2)}$$

Therefore, as a result of putting constant B in order by the least squares method, it turned out that $\sigma_{Y.S.}$ and $\sigma_{T.S.}$ are given by the following equations:



Sample : API 5LX X65 : 609.6 mmϕ×12.7 mm$t$

Fig. 34 Temperature dependence of tensile and yield strength

$$\left.\begin{aligned}\sigma_{Y.S.} &= \sigma_{20(Y.S.)}\exp\{1\,067.9\\&\quad - 251.6 \ln \sigma_{20(Y.S.)}\}\\&\quad \times (1/T - 1/293)\\ \sigma_{T.S.} &= \sigma_{20(T.S.)}\exp\{77.5(1/T - 1/293)\}\end{aligned}\right\} \quad (3)$$

The temperature dependence of ERW pipe strength can be presumed from this equations.

6 Conclusion

The 26 in. ERW mill is one of the largest in the world, and it is capable of manufacturing products with maximum outside diameter of 26 in. (660.4 mm) and maximum wall thickness of 0.63 in. (16.0 mm). Since the start of operation in October, 1978, efforts have been made to improve the hot coil quality, pipe making and welding techniques, as well as nondestructive inspection techniques, resulting in the following.

(1) Thanks to the progress in steelmaking techniques, it has become possible to manufacture hot coil, from Al-Si fully-killed continuous casting steel of high toughness in the low C- and Nb-V group, with rare occurrence of welding defects.

(2) As a result of the improvement in the controlled rolling technique in hot rolling, it has become possible to manufacture hot coil excellent in mechanical properties, gage accuracy and toughness.

(3) Technical improvements in forming and welding and nondestructive inspection in pipe-making have enabled the manufacture of high-test ERW pipe with large outside diameter which has little dispersion on quality in weld zone and excellent toughness.

(4) As a result of various experiments following the start of operation, supplementary strength characteristics (such as Bauschinger effect, yield and burst strengths by internal pressure, tensile strength at lower temperatures, etc.) of pipes manufactured by the 26 in. ERW mill could be quantitatively determined.

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