KAWASAKI STEEL TECHNICAL REPORT
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Recent Manufacturing Techniques of Tube for Boiler - Cr-Mo Electric-Resistance-Welded Tube & Rifled Seamless Tube

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Recent development in our technology of manufacturing boiler tubes is described. Electric resistance welded tubes of 1Cr-1/2Mo steel (STB A22 in the Japanese Industrial Standard) are produced with stability. The production of the Cr-Mo ERW tube of high quality is based on inert gas shielded welding, an automatic heat controlling system and medium-frequency welding. Another technique developed is rifling seamless tubes. Establishment of a cold drawing technique and product-quality controlling system permits production of high quality tubes with excellent rib configuration. Such Cr-Mo ERW and rifled seamless tubes were employed to construct No. 3 West Power Station at Chiba Works of Kawasaki Steel Corporation, which has stationarily supplied electricity since April 1984.

1 Introduction

The manufacture of tubular products at Kawasaki Steel Corporation (KSC) began in 1952 with the electric-resistance-welded (ERW) tubes. The subsequent years saw a series of additions to production facilities, such as those for spiral welded pipe, seamless tube, continuous butt-welded pipe, and UOE pipe. At present, KSC's annual production capacity for tubular products totals 2.5 million. The type of steel available also ranges from carbon steel to stainless steel, both for electric-resistance-welded tubes and seamless tubes.

The manufacture of boiler tube began around 1955. Following grade improvements spurred by the opening of the seamless tube mill, a large tonnage of the products is now shipped for all types of boiler applications in power stations and other industries.

Main features of KSC boiler tubes are:

(1) The use of continuously cast steel desulphurized in the hot-metal stage and RH-degassed reduces segregation in the unit volume of molten steel significantly compared with conventional ingot-cast steel, contributing greatly to the making of clean steel pipe with far more uniform mechanical properties.[1]
(2) A highly automated and systematized pipe-making process minimizes variation in pipe-making conditions, permitting the making of stable quality pipe (e.g. automatic heat input control[2] in ERW pipemaking, and an automated control system for the full rolling line by using a rolling control model in the seamless tube manufacture).
(3) Computer-controlled quality assurance and quality control of the entire manufacturing line from pipemaking through finishing and inspection to shipment.

A study was commenced in 1973 on the feasibility of replacing ingot steel with continuously cast steel as the starting material in pipe-making. This was followed by a series of boiler tube quality tests with assistance of the Technical Division of the Nagasaki Laboratory of Mitsubishi Heavy Industries, Ltd. As a result, the superiority of CC steel was confirmed, with boiler tube made from CC steel enjoying a wide acceptance by power plants, soda recovery plants, and various heat-exchangers.

This report describes STB A22 E · G (1Cr-$\frac{1}{2}$Mo) ERW boiler tubes developed recently for power plants and rifled seamless tubes, with emphasis on manufacturing system and product quality, and outlines actual application results at the West Power Station No. 3 Unit at Chiba Works.

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** Chita Works

2 West Power Station No. 3 Unit at Chiba Works

The No. 3 boiler of the West Power Station at Chiba Works has a 125MW steam power generating capacity. Its efficiency of 92% backed by the world's first large gas heater is a world's record among the gas-fueled boilers. With its high efficiency and energy saving advantages, the boiler also brings the total thermal efficiency of the power plant to 42%. **Figure 1** is an outline of the boiler plant, and **Table 1** its general specifications. In its design, the steam condition (169 kgf/cm^2, 538°C) conventionally used mainly for 375 MW class boilers was adopted, with higher efficiency to be achieved by adopting a cycle for large air drawing capacity. To obtain a higher boiler efficiency, boiler exhaust gas and blast furnace gas are heat-exchanged so as to raise the blast furnace gas temperature for a full recovery of the exhaust gas sensible heat. In the energy-saving phase, the pressurized drafting system is used, and rifled tubes are adopted for the boiler evaporation tubes. This is for an efficient heat-exchanging effect aiming at reduced volume of water circulation so as to economize pumping power consumption.

Steel tubes made by Kawasaki Steel are used for most of the pressure-resisting portions of the plant. Among these are, Cr-Mo ERW tubes (STB A22E · G) and rifled seamless tubes, high quality tubular products developed utilizing KSC's accumulated manufacturing technologies and approved after rigorous testing by the Ministry of International Trade and Industry.

Table 1 Specifications of West Power Station No. 3 Unit at Chiba Works

Type	Mitsubishi controlled circulation radiant reheat pressurized boiler
Fuel	Multi-fuel gas, firing with tangential low NOx-boiler (blast furnace gas, coke-oven gas, basic oxygen converter gas & LPG)
Steam pressure	176/33.8 kgf/cm^2
Steam temperature	541/541°C
Evaporation	430 t/h

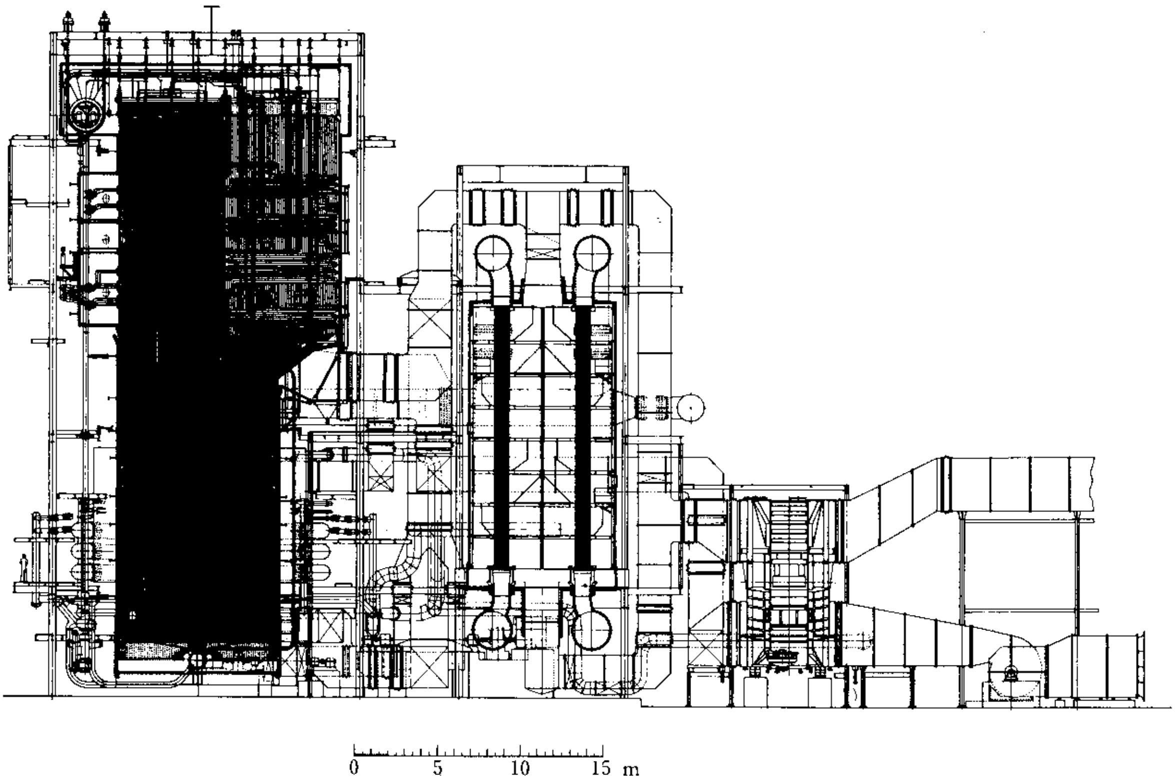


Fig. 1 West Power Station No. 3 Unit of Chiba Works

3 Cr-Mo ERW tube STB A22E · G

The production of Cr-containing low-alloy ERW tube is difficult, because the chromium oxide of high melting point, termed penetrator, is easily formed in the electric-fusion weld zone. In order to prevent the penetrator defect, it is necessary to inhibit the formation of Cr-containing oxide and to squeeze the oxide out from the weld zone. To this end, the following measures can be pointed out as important:

(1) Oxidation preventive measures at the weld zone
(2) Maintenance of optimum weld heat input
(3) Stabilization of molten beads.

To achieve the above, the following new techniques are used in the manufacture of Cr-Mo ERW tube STB A22E · G.

(1) Inert gas shielded welding
(2) Automatic heat input control
(3) Medium frequency welding

This chapter describes these new techniques and the quality of tubes manufactured by using them.

3.1 Manufacturing Techniques

3.1.1 Inert gas shielded welding technique

Ordinarily, welding operations on ERW tubes are performed in the atmosphere, with rolls cooled by water during the hot coil forming process. To a limited extent, therefore, welding cannot be free from the influence of water. In order to keep the weld zone in a non-oxidizing atmosphere, a complete shielding of the weld zone from the atmosphere and forming in moisture-free conditions are necessary. This is the reason for the development of KSC's own technique, called the inert gas shielded welding.

In this technique, a pipe-making in completely moisture-free atmosphere is made possible by using a roll cooling method of KSC's unique development.

3.1.2 Automatic welding heat input control technique

Heat input for ERW tube-making must be properly adjusted to changes in sheet thickness and welding speed. In STB A22E · G, the above requirement is especially strict because the range of allowable heat input is narrow. For this reason, Kawasaki Steel uses an automatic welding heat input control system of its own development.

An outline of the control system is shown in **Fig. 2** and **Table 2**. The control mechanism consists of feed forward and feedback functions. The feed forward heat input control is based on Eq. (1) and aims at adjusting heat input according to changes in sheet thickness and welding speed:

$$\Delta E_{\mathrm{ff}} = E_s\left(A \cdot \frac{t - t_s}{t_s} + B \cdot \frac{V - V_s}{V_s}\right) \quad \cdots\cdots(1)$$

where,

ΔE_{ff}: heat input for feed forward control
E_s: initial heat input
t: thickness of hot coil
V: welding speed
t_s: standard thickness of hot coil
V_s: standard welding speed
A: constant
B: constant

Also, for a higher accuracy control by meeting the changes in impedance efficiency and the shape of hot coil during welding, feedback control using welding temperature and compressing force is performed at the same time.

$$\Delta E_{\mathrm{fb}} = C(\theta - \theta_s) + D \cdot \frac{P - P_s}{P_s} + \Delta E_{\mathrm{fb}}' \quad \cdot(2)$$

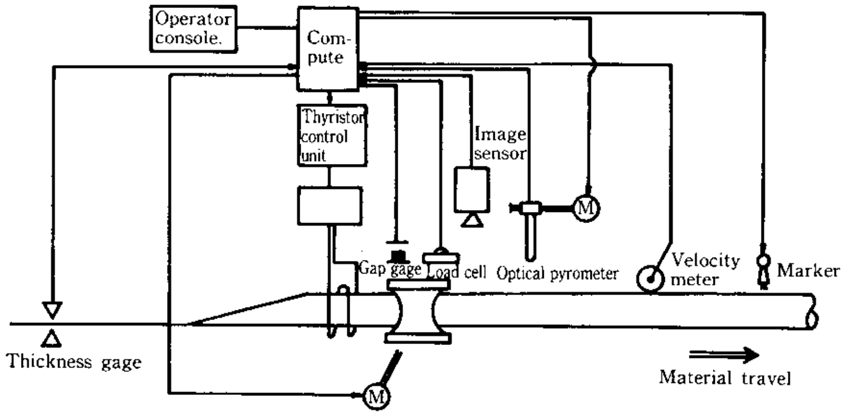


Fig. 2 Automatic heat control system

Table 2 Specifications of equipment for automatic heat control system

Instruments and controllers	Specifications
DDD (Direct digital controller)	MEDAC 16/11 (Micro computer) Main memory: 64 kW Peripheral: console typewriter : logging typewriter
Velocity meter	Pulse generator and counter Range: 0～328 ft/min (0～100 m/min) Accuracy: 0.492 ft/min (0.15 m/min)
Thickness gage	Mechanical flying micrometer Range: 0.00～0.591 in (0.00～15.00 mm) Accuracy: 0.0004 in (0.01 mm)
Optical pyrometer	Glass fiber type two color pyrometer Range: 1 832～3 632 °F (1 000～2 000°C) Accuracy: 50 °F (10°C)
Load cell at squeeze roll	A pair of load cells Range: 0～55 115 lb/unit (25 t/unit) Accuracy: 200 lb (0.1 t)
Gap gage	Gap sensor of eddy current type Range: 0～6 mm Accuracy: 0.05 mm
Image sensor	MOS type Range: 0～50 mm Accuracy: 0.05 mm
Reference of thyristor control unit	Analogue output of DDC Range: 0～10 V Accuracy: 0.1% F.S.

where,

ΔE_{fb}: heat input for feedback control
$\Delta E_{fb}'$: heat input for feedback control (for the preceding one)
θ: welding temperature
P: compressing force
θ_s: standard welding temperature
P_s: standard compressing force
C: coefficient
D: coefficient

In feedback heat input control, 1400°C is used as the standard welding temperature control level. In this temperature range, welding temperature is most sensitive to changes in welding heat input. For this reason, heat input control at this temperature level is most effective in improving control accuracy. **Figure 3** is an example of welding temperature transition considered under two heat input levels. The temperature difference between the two input levels is greatest not immediately after welding but at around 1350°-1450°C, indicating this is the range most suitable for application of heat input control measures.

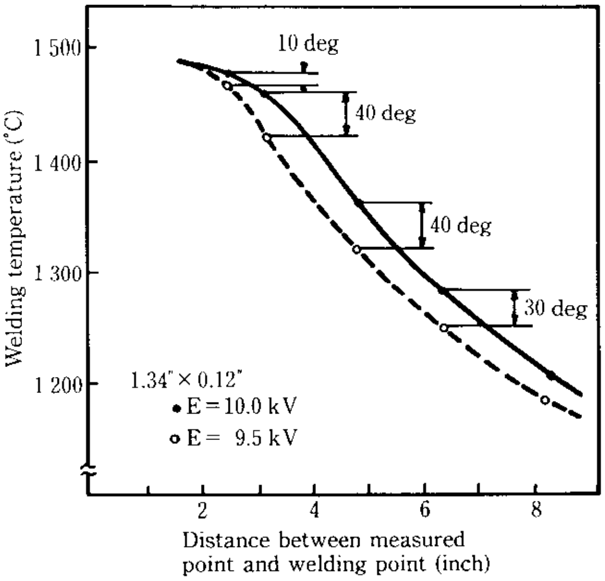


Fig. 3 Example of the transition of welding temperature

A typical example of heat control condition during welding using the above technique is shown in **Fig. 4**. Welding temperature is stable within around ±20°C.

3.1.3 Intermediate frequency welding tehcnique

For ERW tube-making, high frequency (180-450 kHz) is usually used for higher welding efficiency. In the high frequency welding, skin effect is noticeable during heating, and welding current is concentrated at the weld zone corners, which are heated preferentially, and have tendency toward unstable melting bead shape. This is disadvantageous from the standpoint of penetrator prevention, so that a reduction in welding frequency is necessary to stabilize melting bead shape.

Usually, current penetration is given by Eq. (3)

$$\Delta = \frac{1}{2\pi} \times \frac{\varrho}{\mu f} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where,

Δ: current penetration depth
ϱ: proper resistance
μ: specific permeability
f: frequency

The distribution of induced current is obtained by Eq. (4) when the current is approximated with a linear equation:

$$I = I_0 \exp\left(-\frac{x}{\Delta}\right) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where,

I: current density
I_0: surface current density

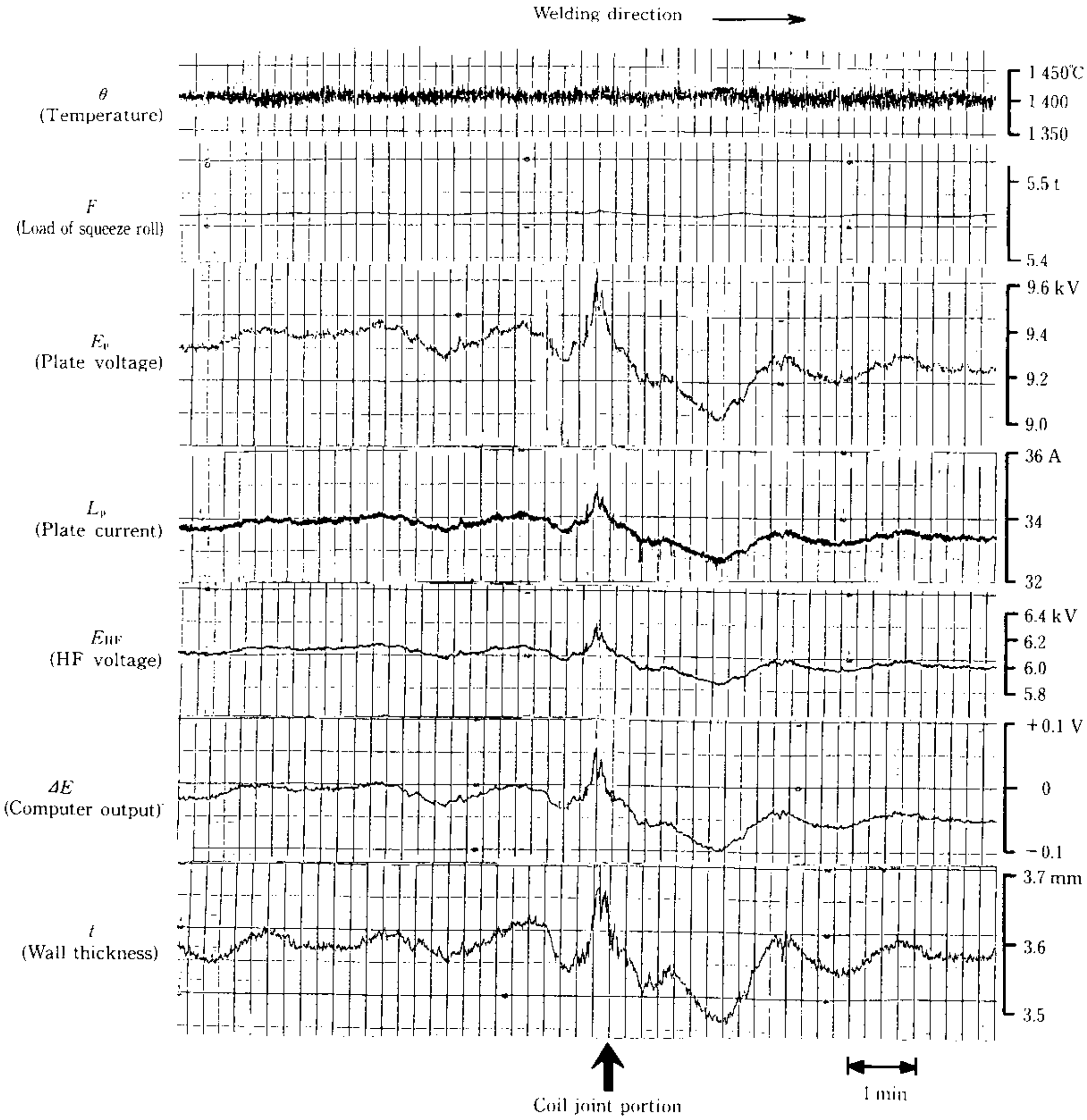


Fig. 4 Welding conditions by means of automatic heat input control techniques

x: position along circumferential direction of the pipe

Δ: current penetration depth

Temperature distribution along circumferential direction of the pipe is calculated by the heat conduction Eq. (5).

$$\gamma c \cdot \frac{\partial T}{\partial t} = K\frac{\partial T}{\partial x} + 0.24I\varrho \quad \cdots\cdots\cdots\cdots (5)$$

where,

γ: density

c: specific heat

T: temperature

K: thermal conductivity

ϱ: proper resistance

t: time

Figure 5 shows an example of a temperature distribution calculation result. As shown in **Fig. 6**, results of experiment show good agreement with the results of calculation. These results are reflected in the intermediate frequency welding technique developed at Kawasaki Steel for the manufacture of STB A22E · G.

Photo 1 compares the shape of melting beads at V-convergence zone under optimum condition between the intermediate frequency welding and the high frequency welding. With the high frequency welding, surface roughness is noticeable, but the surface is smooth and uniform with the intermediate frequency welding.

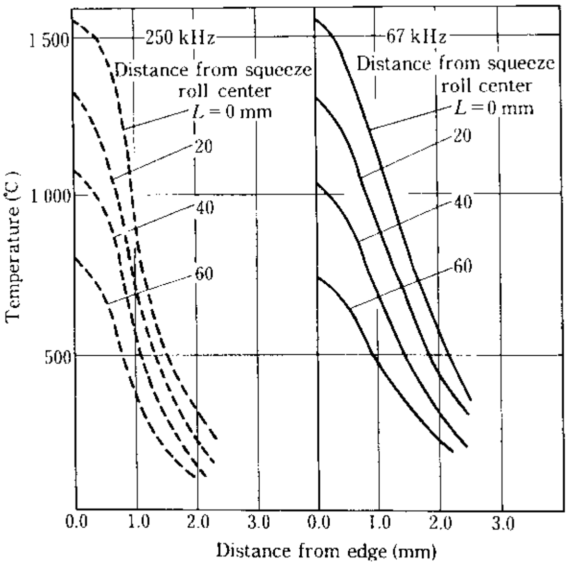


Fig. 5 Temperature distribution

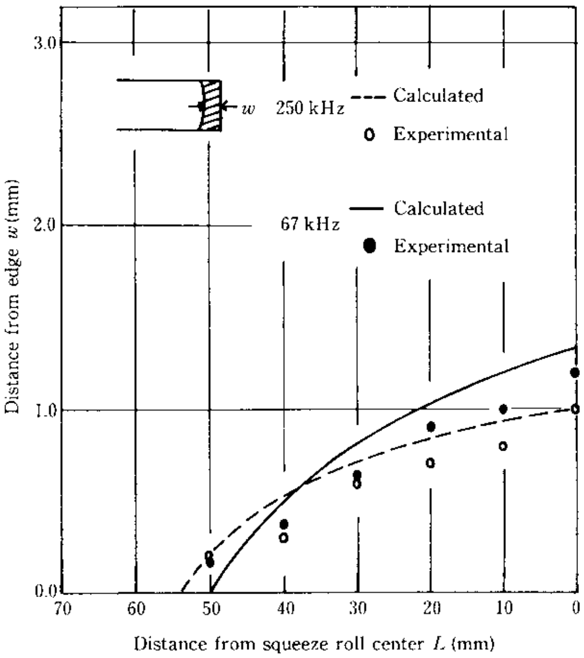
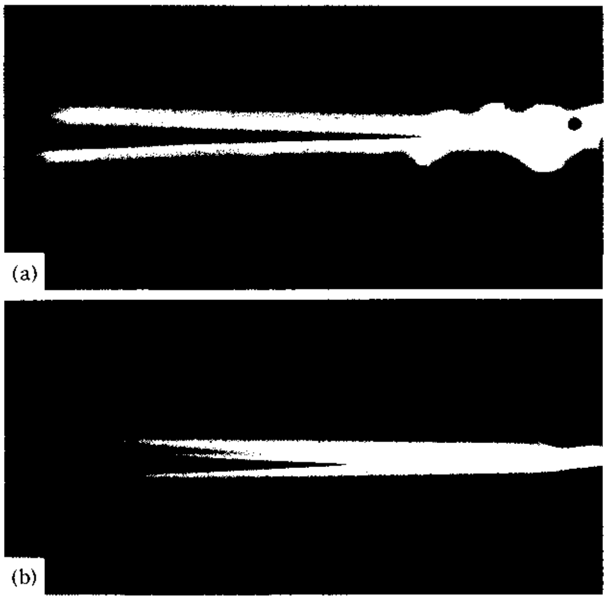


Fig. 6 Change in area of heated zone

Photo 2 compares heat patterns at V-convergence zone. In the high frequency welding where the induction current is concentrated at the corners, there is a difference in the width of the heat affected zone between the thickness center portion and the portion immediately below the outer surface. Contrarily, in the intermediate frequency welding, the HAZ is wide and almost uniformly heated.



a: 250 kHz
b: 67 kHz

Photo 1 Comparison of heating phenomena between 250 kHz and 67 kHz heatings; a view of upper surface of pipe at welding zone

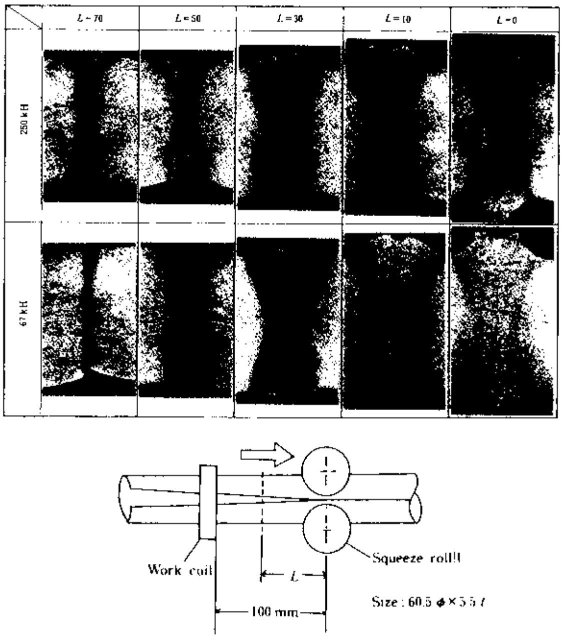


Photo 2 Comparison of heating patterns between high frequency heating and middle frequency heating

3.2 Manufacturing System

The combination of the automatic welding heat input control technique, the intermediate frequency welding technique, and the inert gas shielded welding technique has made it possible to manufacture Cr-containing low alloy steel pipe. In the manufacture of Cr-Mo ERW tube STB A22E · G, these techniques are applied effectively, with rigorous quality control from pipe-making through the finishing process.

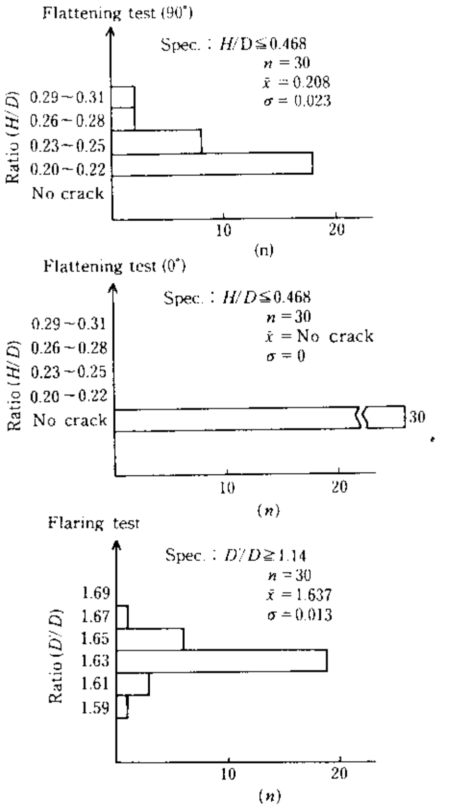


Fig. 7 Flattening and flaring test (STB A22E · G: 48.6 $\phi \times 4.2t$)

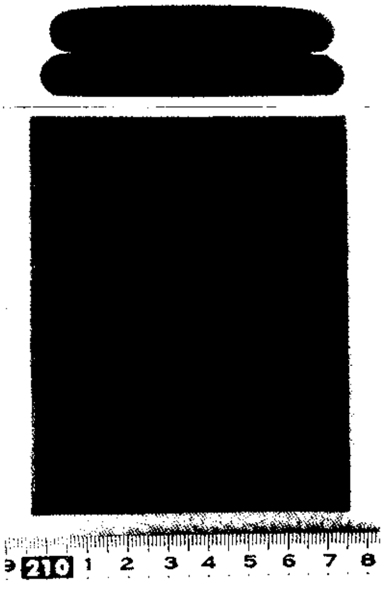


Photo 3 Results of crush test (upper) and reverse flattening test (lower) (STB A22E · G: 48.6 $\phi \times 4.2t$)

3.3 Qualities of Tube

Cr-Mo ERW tube STB A22E · G manufactured under strict quality control is found to have a quality level quite satisfactory to the specifications. **Figure 7** and **Photo 3** show the results of quality tests given to the weld zone, the area on which evaluation of product quality is based. Further, the results of creep test, as shown in **Fig. 8**, are as good as those of seamless tube.

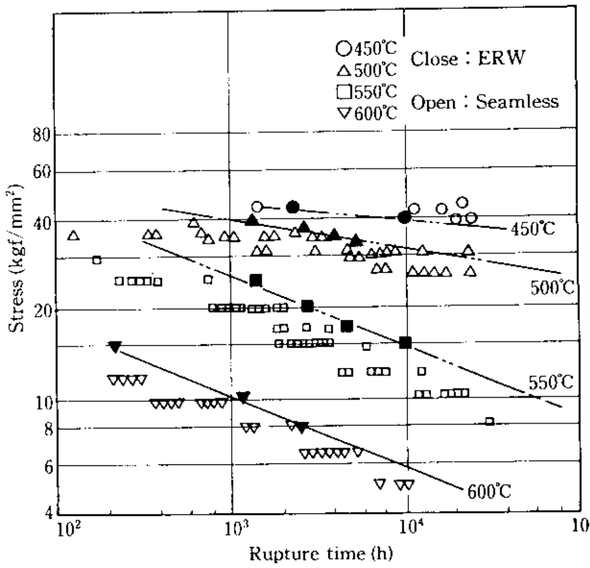


Fig. 8 Results of internal pressure creep rupture test

4 Rifled Seamless Tube

Rifled tube, with a spiral rib throughout the length of the interior surface of the tube for improved heat conductivity (**Photo 4**), is drawing growing attention. The demand for this product is also increasing sharply in line with the recent trend toward larger capacity, higher temperature, and higher pressure boilers. Rifled tube was adopted at the West power station No. 3 unit at the Chiba Works for heat conductivity improvement. The relatively rapid development of the high quality rifled tube to the point of commercial production is largely attributable to KSC's long experience with cold drawing techniques.

The following describes the quality of the rifled tube used for the West Power Station No. 3 Unit, with emphasis on the dimensions and shape, and also outlines the cold drawing technique.

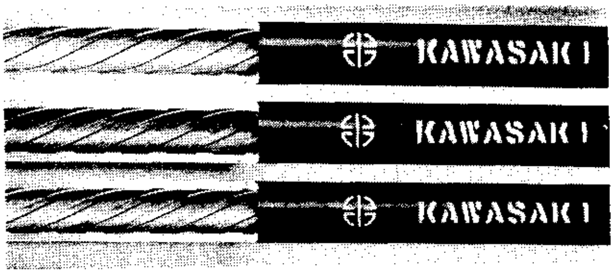


Photo 4 Inside view of rifled tube

4.1 Forming of Rifled Ribs

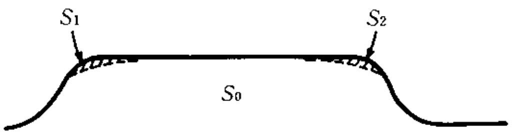
In the processing of the rifled tube, mother pipe is squeezed externally by a die set in a die stand placed at the center of a cold drawn bench, while a grooved plug placed inside forms a spiral ribs on the internal surface. The plug turns freely, which is an important element in the design of the mechanism. On the rifle forming, the plug contour is a large factor in determining product characteristics such as rib height and rib shape, especially, rib corner and lead angle.

Plug shape has been the subject of independent study by various makers. Kawasaki Steel, as a result of its study and experiments, has succeeded in the development of a plug shape which assures an easy forming of rib height, a higher fill up ratio of rib configuration, and a complete prevention of galling. The plugs thus developed are used for the manufacture of the rifled tube with varied rifling shapes.

4.2 Rib Formability in Rifling

Rib formability in rifling is affected by such customer specifications as wall thickness/outside diameter ratio, rib number, rib height, ratio of rib width, and by manufacturing factors such as diameter reduction ratio at drawing, reduction in wall thickness, reduction in area, plug position, plug shape, die profile, and drawing speed.

Rib height and rib configuration fill up ratio can be regarded as important factors in a quantitative evaluation of the influence of each factor. Here, the rib configuration fill up ratio K is a parameter introduced to evaluate the lack of fill at rib corner, and it is defined by the equation shown in **Fig. 9**.



$$K=\frac{S_0-(S_1+S_2)}{S_0}$$

S: cross section area of rib

Fig. 9 Definition of K

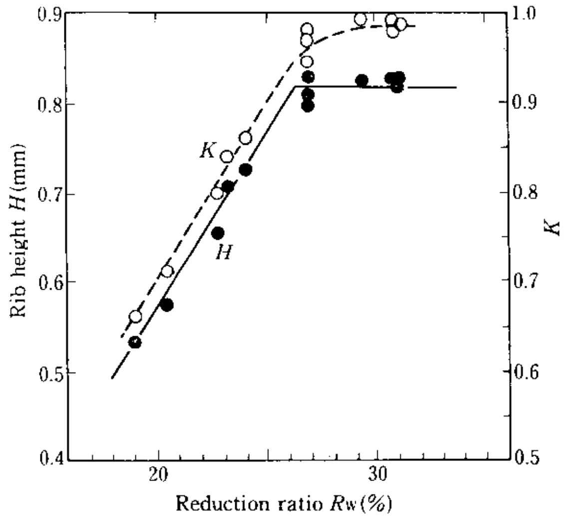


Fig. 10 Relation between reduction ratio, rib height, and K

(1) Rib height H
The relationship between the thickness reduction ratio R_w at rib bottom and rib height H is shown in **Fig. 10**. The area reduction ratio is changed by changing the thickness of the mother pipe for rifling. During drawing in the low area reduction zone, rib height increases linearly, and comes to conform perfectly to the desired rib shape as it is blocked by the plug grooves. Thus, in the graph in Fig. 10, the full rib height is indicated by a flat line.

(2) Rib configuration fill up ratio K
Deformation resistance during rifling work changes greatly according to pre-rifling annealing conditions. To increase rib configuration fill up ratio, therefore, it is important that the mother pipe be softened as much as possible.

As shown in Fig. 10, a large thickness reduction ratio is important in improving rib fill up ratio, as in improving rib height. A higher wall reduction ratio than necessary leads to an increased drawing force by the draw bench, and further to plug galling; therefore, an optimum value should be observed.

4.3 Manufacturing System

Compared with ordinary cold rolled finished products, rifled tubes are subjected to an exceptionally rigid working; therefore, special quality examinations, as shown in **Table 3**, are required during the manufacture and inspection stages. Mother pipe is hot-finished on the Mannesmann mandrel mill, with its quality verified by NDI and other rigid inspections. Cold drawing is performed a number of times as necessary to reach specified mother pipe dimensions for the rifled tube. Then, pretreatment is given again, and rifling is performed by

Table 3 Manufacturing process and quality control

Process	Equipment	Main quality control item
Hot rolling	Mandrel mill	1. Heating temperature 2. Roll setting 3. Dimension
Mother tube	Visual inspection Eddy current inspection Magnetic particle inspection	1. Reference standard 2. Surface condition 3. Dimension
Cold drawing	Drawn bench	1. Tool dimension 2. Drawing speed
Softening	Continuous heat treatment furnace	1. Heating temperature 2. Heating time 3. Atmospheric gas composition
Nondestructive examination	Visual inspection Ultrasonic tester	1. Reference standard 2. Surface condition 3. Dimension
Rifling	Drawn bench Cone-tracer	1. Tool dimension 2. Drawing speed 3. Visual check of drawn tube 4. Configuration check by cone-tracer
Heat treatment	Continuous heat treatment furnace	1. Heating temperature 2. Heating time 3. Atmospheric gas composition
Hydrostatic test	Hydrostatic testing machine	1. Test pressure 2. Keeping time
Nondestructive examination	Eddy current tester Ultrasonic tester	1. Reference standard 2. Surface condition
Final inspection	Visual inspection Fiber-scope	1.Dimensional checking (OD, WT, Length, ID) 2. Material identification test 3. Configuration & inside surface condition check by fiber-scope
Testing	Testing machine Microscope	1. Chemical composition 2. Tension test 3. Hardness test 4. Flattening test 5. Flaring test 6. Reverse flattening test 7. Rib configuration 8. Microstructure
Marking and coating		1. Marking items
Packing		

cold drawing.

Finished products after rifling undergo a proper heat treatment to assure material strength and then are subjected to a rigorous inspection.

The following three procedures have been adopted as advanced on-line quality assurance measures:

(1) Examination of plug appearance at each drawing during rifling

(2) Examination of finished product shape using con-tracer

(3) Examination of internal surface of the tube using fiberscope

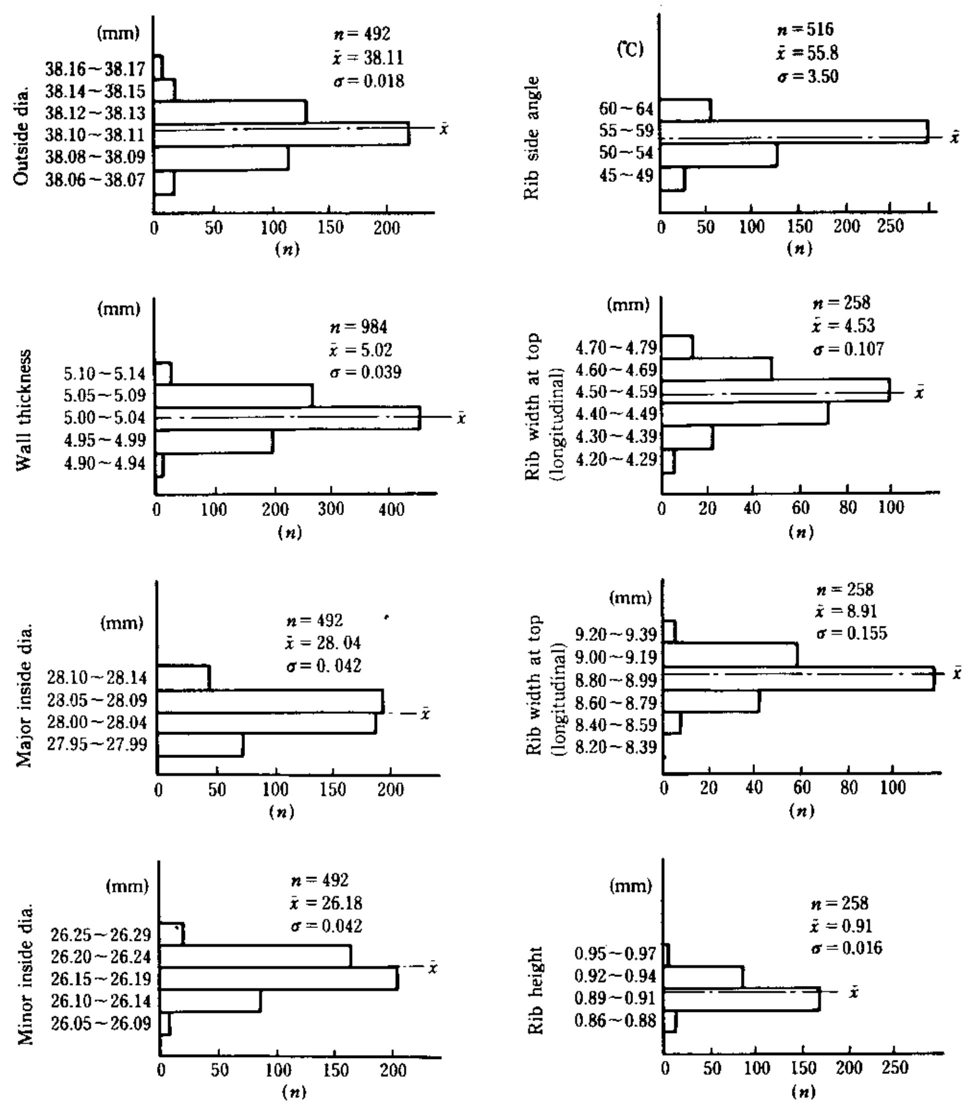


Fig. 11 Histogram of rifled tube dimension

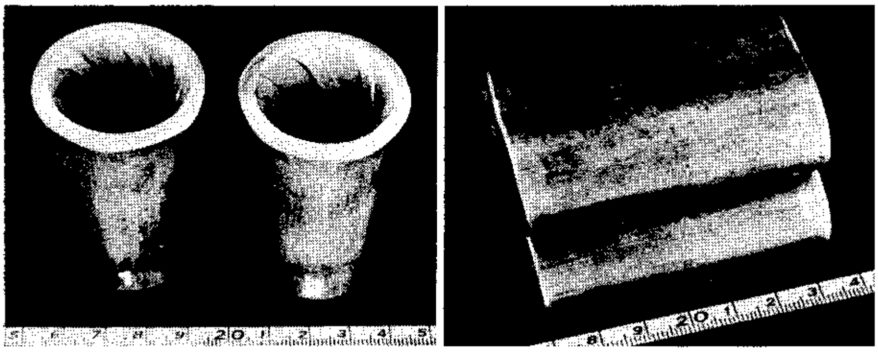
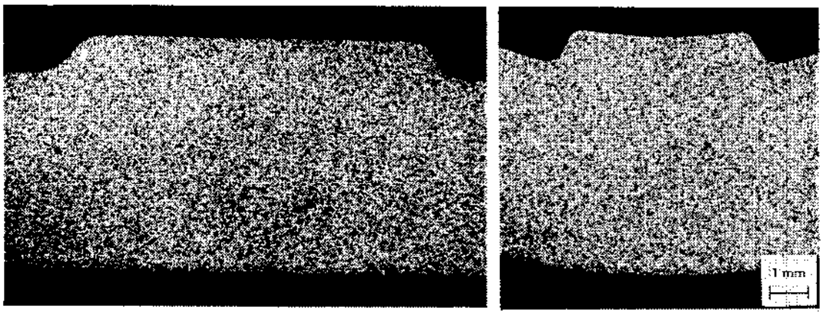


Photo 5 Views of specimens after flattening test (right) and flaring test (left)

4.4 An Outline of Quality

The quality of rifled tubes used for the West Power Station No. 3 Unit has proven highly satisfactory. As an example of the quality of rifled tube, dimension histograms of typical product factors are shown in **Fig. 11.** Appearance after a commercial production test is shown in **Photo 5**, and the macrostructure and microstructure of a rib crossection in **Photos 6** and **7**, respectively. All are satisfactory.



Longitudinal section Cross section

Photo 6 Macrostructure of configuration

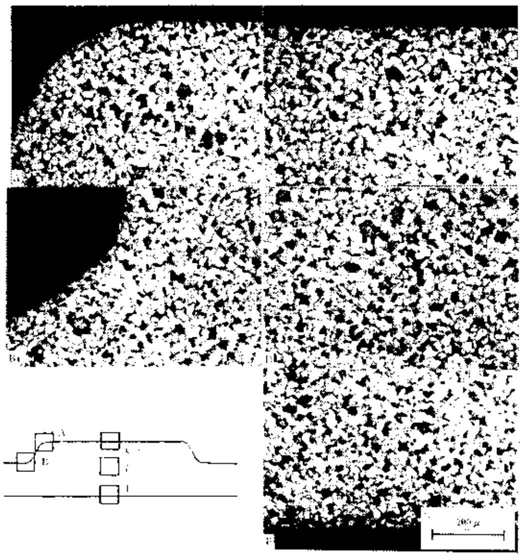


Photo 7 Microstructure of a cross section of the rifled tube containing 0.20%C

5 Summary

The manufacturing techniques and the quality level of boiler tubes, especially Cr-Mo ERW tubes STB A22E · G (1Cr-$\frac{1}{2}$Mo steel) and rifled tubes, have been introduced. These techniques are reflected in the manufacture of not only boiler tubes but also other tubular products, contributing immensely to enhancing the levels of steel pipe manufacturing techniques.

The West Power Station No. 3 Unit, whose boiler tubes were all manufactured by these techniques, began operation in April 1984 and has since been running very smoothly.

The authors wish to express their sincere thanks to all members of various sections of Power Department, Kobe Shipyard, Mitsubishi Heavy Industries, Ltd. for their valuable advice and the assistance extended during KSC's adoption of Cr-Mo ERW tubes and rifled tubes to the West Power Station No. 3 Unit.

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