KAWASAKI STEEL TECHNICAL REPORT
No.13 (September 1985)

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Norio Sumita, Yukio Oguchi, Tetsuya Fujii, Toshihiko Emi, Arata Ueda, Takuo Imai

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Mass production test for the 250-t PM process was carried out on the commercial production line and the following results were obtained: (1) Stirring intensity of the melt is equal to or better than that of the RH degassing process. (2) The rate of deoxidization and yield of alloying elements are excellent, equivalent to those of the RH process. (3) The operation cost is one eighth that of the RH process. (4) The investment cost also is cheap and estimated to be one-fifth to one-tenth that of the RH process.

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Ladle Refining Performance of Pulsating Mixing (PM) Process with 250-t BOF Melts*



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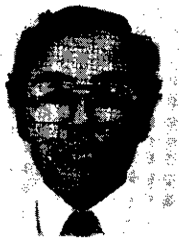


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Mass production test for the 250-t PM process was carried out on the commercial production line and the following results were obtained:
(1) Stirring intensity of the melt is equal to or better than that of the RH degassing process.
(2) The rate of deoxidation and yield of alloying elements are excellent, equivalent to those of the RH process.
(3) The operation cost is one eighth that of the RH process
(4) The investment cost also is cheap and estimated to be one-fifth to one-tenth that of the RH process

1 Introduction

With user requirements for steel products getting increasingly severe, various ladle refining processes have recently been developed to improve and stabilize the quality of steel products. Vacuum degassing processes represented by the RH and DH processes pose problems in terms of economy, despite their refining capability almost satisfactory in meeting quality requirements for mass-produced steel products. Both equipment costs and treatment costs, however, are high.

Argon gas bubbling treatment, based on the principle of stirring by injected gas, has been made practical as a ladle refining process which does not require vacuum refining (i.e., the simple ladle refining processes). The treatment cost of this process is low; the operation method simple. Furthermore, this process has the advantage that the drop in molten steel temperature caused by the treatment is small.

On the other hand, this process has the drawback that a strong strirring of molten steel is limited to only near the bath surface in the ladle, while the strirring at the ladle bottom is relatively weak. In addition, the intensive mixing of the slag on the bath surface with molten steel is apt to cause the reoxidizing and rephosphorizing of the molten steel due to the slag flowing into the ladle from a primary refining furnace such as a converter. Therefore, special considerations such as improvement of slag properties are necessary to improve the effectiveness of this treatment.

To solve these problems with the conventional simple ladle refining processes, Kawasaki Steel developed a new simple ladle refining process called the pulsating mixing (PM) process, which, excepting the function of vacuum refining, has the same functions as the vacuum degassing processes such as the RH and DH processes.

Furthermore, in both treatment costs and the equipment costs, the PM process is far lower than those of the vacuum degassing processes. The development of this process began with cold model experiments and related

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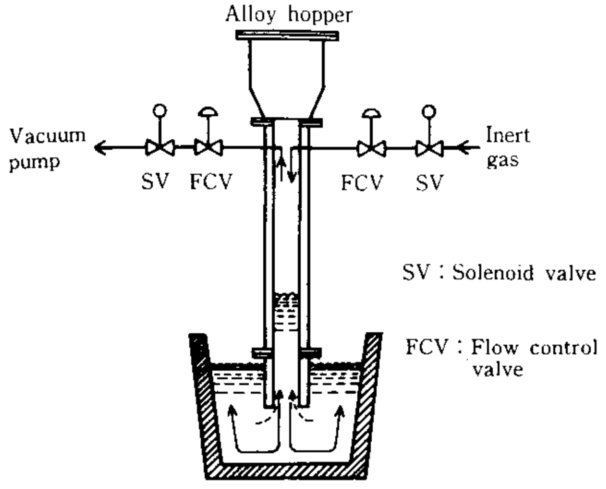


Fig. 1 Principle of PM process

theoretical analyses[1], followed by the clarification of operation results and metallurgical characteristics of the process in a pilot plant[2]. Development was completed with an increase in the ladle capacity to 250 t and mass-production experiments.

2 Principle of PM Process

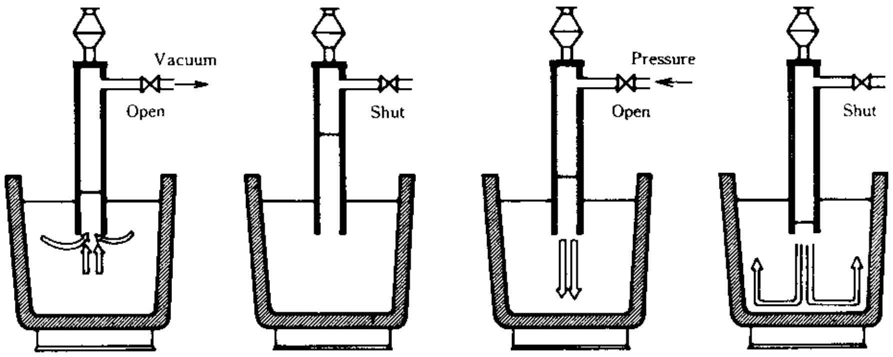
The argon gas bubbling treatment, based on the principle of injected gas stirring, provides sufficient mixing energy compared with the RH and DH processes. There is a marked difference in the flow pattern of molten steel in the ladle with the argon bubbling process and the RH and DH processes. Results of water model experiments and numerical calculations using Navier Stokes' equation reveal that strongly stirred regions exist only near the bath surface in the argon bubbling process; that is, the molten steel near the bath surface in the ladle is strongly stirred and the stirring force decreases with increasing bath depth.[1]. In the RH and DH processes, however, the molten steel at the ladle bottom is most strongly stirred, and the stirring force near the bath surface is relatively weak. It may be said that the injected gas stirring is a process susceptible to the influence of the slag on the bath surface, such as the rephosphorization and reoxidation of the molten steel.

The pulsating mixing (PM) process for ladle refining shown in **Fig. 1** was developed in consideration of this difference in the stirring pattern. As shown in **Fig. 2**, mixing energy in the PM process is applied by periodic variations in the gas pressure in the cylinder. Molten steel is caused to flow into, and out of, the cylinder as the gas pressure in the cylinder is reduced from, and increased over, the atmospheric pressure, respectively, in a high speed cycle.

The kinetic energy of the molten steel flowing out of the cylinder at a high velocity is thereby utilized to stir the molten steel.

3 Outline of Construction and Functions of PM Equipment

PM equipment for treating a 250-t melt was constructed based on the results[1-3] of investigation into the operation performance and metallurgical characteristics of the PM process in experiments with a 100-t facility. The construction and basic specifications of this 250-t facility are shown in **Fig. 3** and **Table 1**, respectively. This equipment was installed along the steel ladle transfer line between the No. 4 BOF and the continuous caster in the No. 2 steelmaking shop at Mizushima Works. A general view of this equipment is shown in **Photo 1**. The cylinder of the equipment is installed on the arm of the turret. When the steel ladle arrives, on rails, at the PM treatment area, the arm of the turret rotates to insert the cylinder into the molten steel in the ladle. Low-purity nitrogen gas fed from a valve stand is used to repeatedly pressurize the cylinder, with the gas evacuated by a water-sealed Roots pump. Alloy hoppers are installed on top of the cylinder so that alloys can be added to the



Suction by reducing pressure

Upper limit

Ejection by pressurized gas

Lower limit

Fig. 2 Stirring principle of the PM process

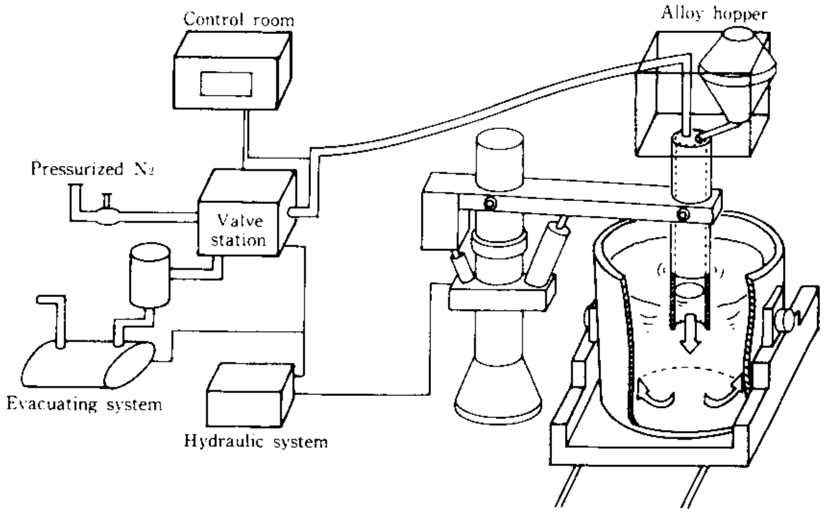


Fig. 3 PM facilities for ladle refining of 250 t melt

Table 1 Basic dimensions of PM facility

Ladle capacity	250 t
Refractory tube	600 mm inside dia.
Hydraulic swing arm system	rev. 180° (2 rpm) lift 2 500 mm (1 000 mm/min)
Alloy hopper	Al, C, 1 000 kg each
Pressurizing gas	N_2
Pressure range	0.2-1.4 atm
Pulsating cycle	3-8 s
Stirring energy	10 W/t · steel

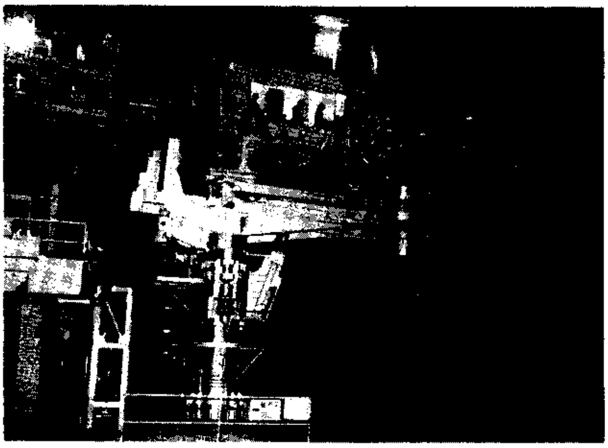


Photo 1 Elevation of 250 t PM process

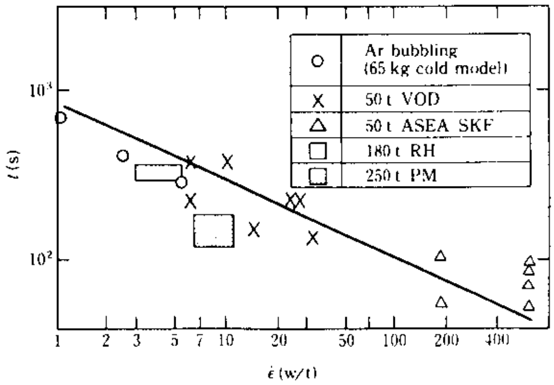


Fig. 4 Perfect mixing time t for 250 t PM process compared with other processes ($\dot{\varepsilon}$: input energy for stirring)

molten steel in the cylinder during treatment in order to modify its chemical composition. All these operations are controlled from the control room in both manual and automatic modes.

The cylinder is 600 mm in inside diameter and 3500 mm in total length and is composed of a shell and refractories. The turning angle of the arm is 180° and the vertical stroke is 2 500 mm. Two alloy hoppers each with a 1 m^3 inner volume, are provided; aluminum and carbon are the alloys mainly used for control of chemical composition. Low-purity nitrogen gas is used as the pressurizing gas. The water-sealed Roots pump provided for depressurization has an evacuation capacity of 66 m^3/min. The pressure range in the cylinder is from 0.2 to 1.4 atm, with a pressure cycle ranging from 3 to 8 sec. As shown in **Fig. 4**, the mixing energy given to molten steel is 10 W/t · steel. The gas pressure in the cylinder is automatically controlled to the proper level at any time by a sequence controller. Two pressure detection equipment systems are installed as a measure to increase the reliability of pressure signals. An example of a pressure signal is shown in **Fig. 5**.

The features of PM equipment are summarized in the following:

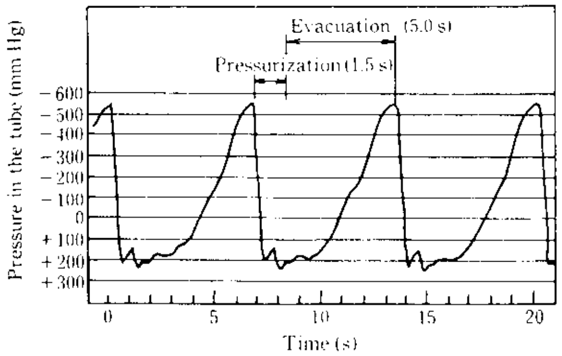


Fig. 5 Example of a time chart for pressure change

(1) This equipment has the same functions as conventional RH and DH degassing equipment in terms of cleaning of molten steel and adjustment of alloying elements, with the exception of the refining functions of hydrogen removal and decarburization.
(2) Since the equipment is simple in construction, equipment costs and treatment costs are low.
(3) The operating method is simple, and the stirring force applied to the molten steel is easily controlled.
(4) The molten steel temperature drop during treatment is small because the contact area between the molten steel and the refractory is small.

4 Refining Effects of PM Process

4.1 Experimental Method

To clarify the refining effects of the PM process, experiments were conducted on the deoxidation treatment of molten steel and composition adjustment by alloy addition.[4-6]

The refining effect was investigated using mainly low-carbon aluminum-killed steels for cold-rolled sheets and aluminum-silicon-killed steels for electric-resistance-welded (ERW) pipe. **Table 2** gives typical examples of the chemical compositions of these steels.

After the completion of ordinary converter blowing, molten steel, to which alloys and a deoxidizer had been added during tapping, was transported to the PM treatment area and subjected to the PM treatment for 10 to 15 min. After the treatment, the molten steel was cast by continuous caster and then worked into products. The distribution of large nonmetallic inclusions in slabs was measured for a portion of the aluminum-silicon-killed steels. In addition, ultrasonic testing of products was carried out.

4.2 Time Required for Uniform Mixing

The uniform mixing time was measured to evaluate the molten steel stirring force, which is considered one of the most important functions of ladle refining equipment. Copper, which shows a relatively high dissolution rate in molten steel and is not greatly affected by chemical reactions, was used as a tracer and added to the molten steel in the cylinder during the PM treatment. Analysis samples were continuously taken from near the bath surface upon addition, and changes in the copper concentration with time were determined. Results of this determination are shown in **Fig. 6**. When the pressurized gas pressure is low and the stirring force is insufficient, the copper concentration increases linearly and reaches a constant value in about 200 sec, at which time uniform mixing is accomplished. When the stirring force is sufficient, the copper concentration reaches a peak value and strong circulated streams are supposed to be formed. In this case, the uniform mixing time is about 100 to 200 sec.

Table 3 gives a comparison with the measurements of uniform mixing time in other representative refining processes. In spite of the simple construction of the equipment, the PM process provides the second greatest stirring force, following only the ASEA-SKF process. Thus, the PM equipment is judged to be an excellent

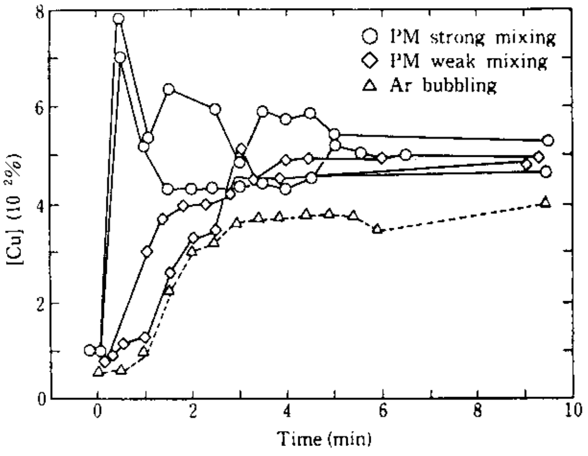


Fig. 6 Change in Cu concentration after addition

Table 2 Chemical composition of steel for deoxidation experiments (%)

	C	Si	Mn	P	S	Al
Al killed	0.05~0.01	0.01~0.05	0.15~0.60	<0.025	<0.020	0.01~0.05
Al-Si killed	0.16~0.20	0.10~0.30	0.50~0.80	<0.020	<0.010	0.03~0.05

Table 3 Comparison of mixing time in various processes

(sec)

PM	RH	DH	ASEA-SKF	VOD
100～200	150～400	150～300	80～100	120～360

molten steel stirring unit.

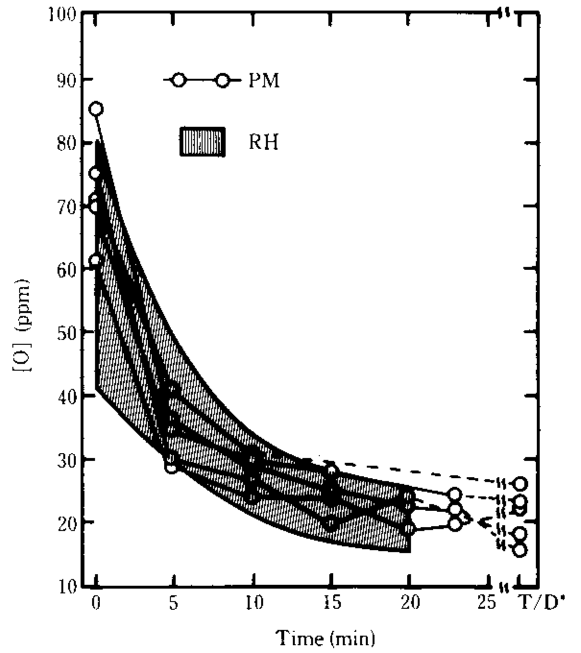
4.3 Deoxidation Treatment

4.3.1 Deoxidation rate

Figure 7 shows representative examples of the deoxidation curve of an aluminum-silicon-killed steel, obtained during 100-t melt experiments with the PM equipment.[1-3] The rate constant of deoxidation, K, is 0.08 to 0.1 min^{-1} and the oxygen concentration reached, $[O]_f$, 15 to 25 min after the start of treatment, ranges from 18 to 24 ppm. In typical analytical values of molten steel in the tundish during continuous casting, the oxygen concentration $[O]_D$, is 21 ppm, almost the same level as in the RH degassing treatment. When 250-t melts were treated, $[O]_f$ after the treatment and $[O]_D$ during continuous casting showed almost the same results as with 100-t melts.

4.3.2 Oxygen concentration in CC tundish

With respect to the oxygen concentration $[O]_D$ in the CC tundish, an investigation was made into the deoxidation effect of the PM treatment. **Figures 8** and **9** show the $[O]_D$ distribution of a low-carbon aluminum-killed steel and an aluminum-silicon-killed steel, respectively. In the aluminum-killed steel, $[O]_D$ shows smaller variations on the high value side in the PM process than in the argon bubbling process, and the average value is 6 ppm lower than in the argon bubbling process. It can be seen that the PM process is more stable than the argon bubbling process.



*Samples at tundish (after approx. 50-60 min)

Fig. 7 Deoxidation curves for aluminum-silicon killed steel

The average $[O]_D$ of the aluminum-silicon-killed steel is 18.3 ppm, the same level as obtained by the RH degassing treatment.

From the above, it was judged that the deoxidation capacity of the PM process is superior to that of the argon bubbling process and is equal to that of the RH degassing process.

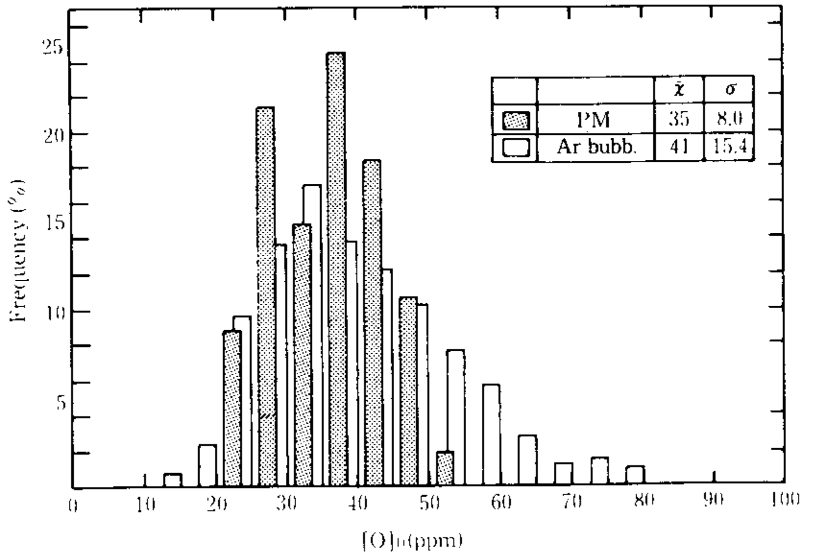


Fig. 8 Example of oxygen content of melt in CC-tundish (low carbon aluminum killed steel, 0.01-0.025% Al)

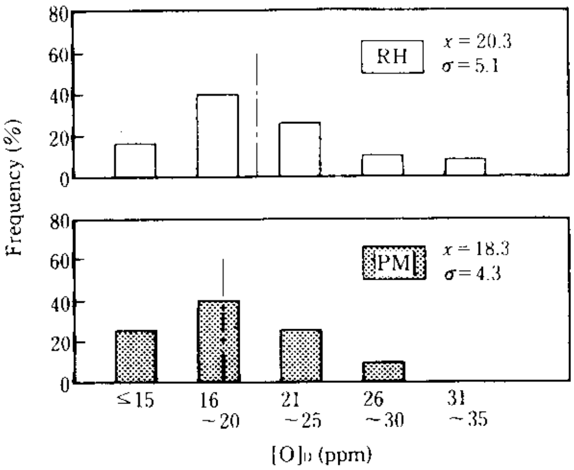


Fig. 9 Example of oxygen content of melt in CC-tundish (Al-Si killed)

4.3.3 Effect of slag composition on deoxidation treatment

The relationship between $[O]_D$ and the iron content of slag, (T. Fe), which is an index of the oxygen potential of slag, was determined for a low-carbon aluminum-killed steel, in order to investigate the effect on the deoxidation treatment of slag on the ladle bath surface. Results of this investigation are shown in **Fig. 10**. It is apparent from this figure that in the PM process, (T. Fe) has a small effect on $[O]_D$, which takes low stable values. With argon bubbling, $[O]_D$ shows large variations and (T. Fe) has a great effect.

From this, the PM process is judged to be less susceptible to the influence of the slag on the bath surface.

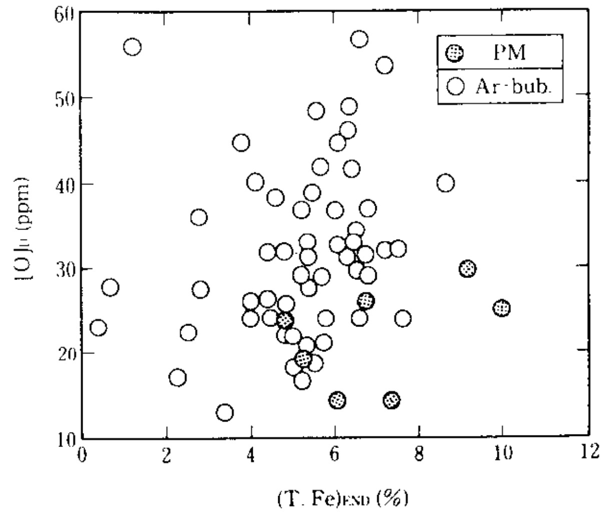


Fig. 10 Relation between (T. Fe) content in slag after treatment and oxygen content of melt in CC-tundish (Al-killed, 0.03–0.05% Al)

4.3.4 Effect of pressurized gas volume

The pressurized gas volume is used as an index of the molten steel stirring force. **Figure 11** shows the relationship between the pressurized gas volume Q per cycle and $[O]_D$. The $[O]_D$ decreases with increasing Q. To reduce $[O]_D$ to 30 ppm or less, a pressurized gas volume of 0.8 Nm^3/cycle or more is necessary.

4.4 Alloy Addition

As with the RH and DH processes, alloy addition during the PM treatment gives excellent results in terms of yield of addition, for the following reasons:

(1) The gas in the cylinder is inert.

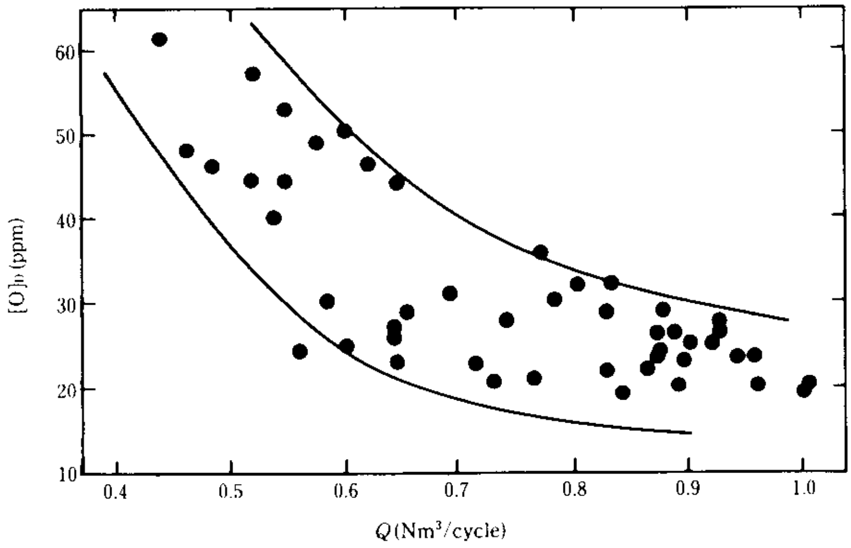


Fig. 11 Effect of N_2 gas consumption on oxygen content of melt in CC-tundish

(2) Oxidizing slag does not flow in.
(3) Added alloys are carried by molten steel streams to the ladle bottom.

Therefore, an investigation was made into the yield with addition of aluminum, carbon, titanium, and boron to determine the suitability of the alloying element adjustment function of the PM process.

4.4.1 Addition of aluminum

Experiments concerning composition adjustment using aluminum were conducted, with the greater portion of aluminum added during converter tapping and only small amounts (about 0.1 to 0.6 kg/t · steel) added during PM treatment for composition adjustment. **Figure 12** shows the relationship between the amount of aluminum added, W_{Al}, and the increase in aluminum concentration, Δ[Al]. Compared to results with the argon bubbling process, the increase in the aluminum concentration, Δ[Al], is large for addition of an equal amount of aluminum added, W_{Al}, and variations are small.

The yield of addition of aluminum, Y, is calculated using Eq. (1):

$$Y = (\Delta[\mathrm{Al}] + \alpha \cdot t) \times \frac{W}{W_{\mathrm{Al}}} \times 100 \quad \cdots\cdots (1)$$

where

Y: Yield of addition of aluminum (%)
Δ[Al]: Difference in aluminum concentration before and after the treatment (%)
α: Rate of oxidation loss of aluminum (% · min^{-1})
t: Treatment time (min)
W: Amount of molten steel (kg)
W_{Al}: Amount of aluminum added (kg)

If the measured value mentioned below (9.0 × 10^{-4}% · min^{-1}) is used as the value of α, the yield of addition is 90% or more, which is equal to the value obtained with the RH process.

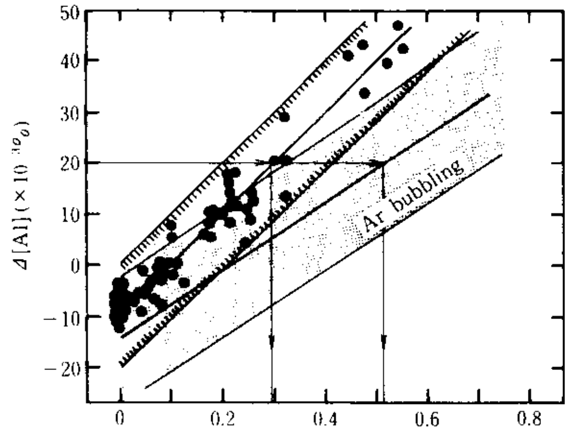


Fig. 12 Relation between the increase, Δ[Al], of contents and amount, W_{Al}, of Al addition (Al saving by PM process is about 0.2 kg/t for trimming 0.020%)

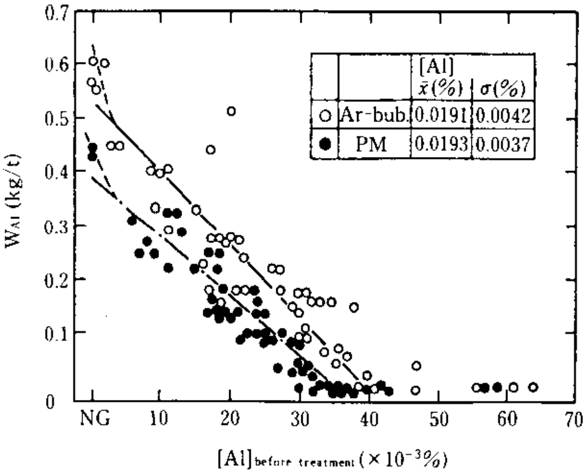


Fig. 13 Relation between Al content before treatment and amount of Al addition required

Figure 13 shows the relationship between [Al] before treatment and the amount of aluminum addition, W_{Al}, required by the PM process to produce steel of grades with aluminum contents of 0.01 to 0.03%. Compared to the argon bubbling process, the amount of aluminum added, W_{Al}, can be reduced by 0.1 kg/t · steel in the PM process. The hitting accuracy of the target [Al] upon completion of the treatment is 0.0055% at σ (σ is standard deviation). Thus, aluminum concentration can be adjusted with high accuracy.

4.4.2 Addition of carbon

Figure 14 shows the relationship between the amount of carbon added and the increase in carbon concentration when carbon concentration is adjusted during the PM treatment. The yield of addition for carbon is almost 100%. The carbon concentration can

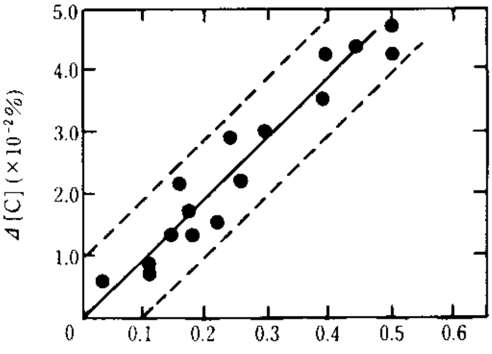


Fig. 14 Relation between the increase, Δ[C], of C content, and amount, W_{C}, of carbon addition by PM process

be adjusted within ±0.01% of the target [C] value.

4.4.3 Addition of other ferroalloys

When special elements such as titanium, niobium, and boron were added during the PM treatment as Fe-Ti, Fe-Nb and Fe-B alloys, the yield of addition ranged from 81 to 100%, showing almost the same level as with the RH process.

It was ascertained from these experimental results that the alloying element adjusting function of the PM process is equivalent to that of the RH process and that the yield of addition obtained in the PM process is equivalent to that obtained when alloys are added under vacuum.

4.5 Changes in Components during PM Treatment

The mode of stirring molten steel in the ladle in the PM process is similar to that with the RH process: The PM process also shows low susceptibility to the influence of slag on the bath surface. Therefore, effects of changes in the contents of alloying elements and impurity elements were investigated to ascertain the effect of the PM process in preventing the reoxidation and rephosphorization of molten steel by slag.

4.5.1 Rate of oxidation loss of aluminum

The rate of oxidation loss of soluble aluminum, Al_{sol}, during the PM treatment was determined in heats in which the entire quantity of aluminum was added during converter tapping and none during the PM treatment. The average rate of oxidation loss of aluminum was $9.0 \times 10^{-4}\% \cdot min^{-1}$. This value is about half the value obtained in ordinary argon bubbling and almost equal to the $1.0 \times 10^{-3}\% \cdot min^{-1}$ in the RH process. Thus, the PM process may be said to be low in susceptibility to reoxidation by slag.

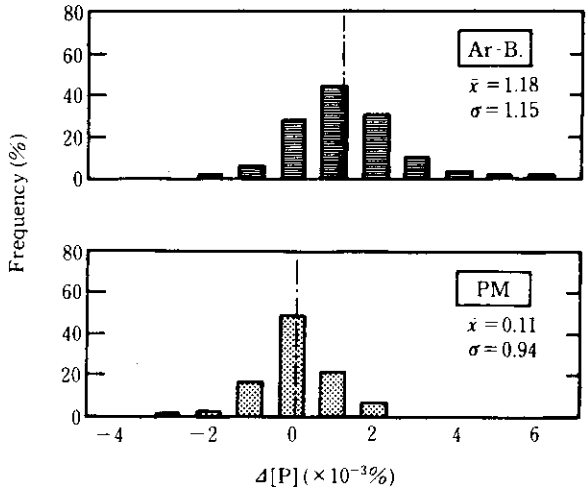


Fig. 15 Distribution of phosphorus pick-up

4.5.2 Amount of phosphorus pick-up

Figure 15 shows a comparison of amounts of phosphorus pick-up during treatment by the PM process and the argon bubbling process, respectively. The amount of phosphorus pick-up after 8- to 12-min treatment is $1.1 \times 10^{-4}\%$ on average, which is 1/10 the amount obtained in the argon bubbling process. It is judged that rephosphorization virtually does not exist.

4.5.3 Changes in nitrogen content

Figure 16 shows the distribution of nitrogen pick-up during PM treatment. Although low-purity nitrogen gas ($\%N_2 = 97$ to 98%, $O_2 = 2$ to 3%) is used as the pressurizing gas, the increase in nitrogen content caused by the PM treatment is negligible at 0.9 ppm on average.

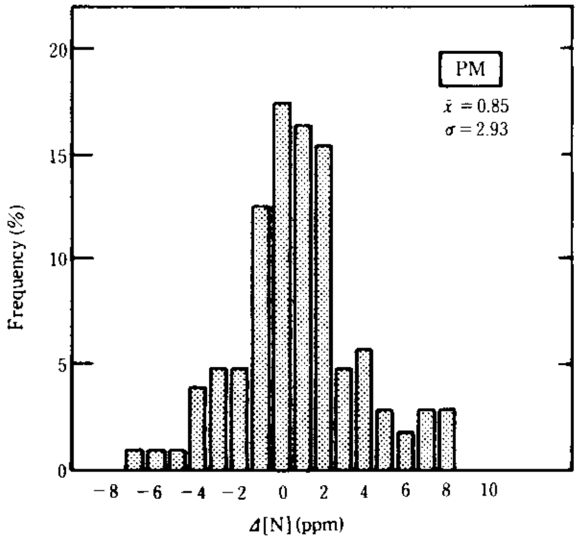


Fig. 16 Distribution of nitrogen pick-up by PM treatment

4.5.4 Changes in contents of other elements

The oxidation loss of manganese after 8- to 12-min treatment is $0.33 \times 10^{-2}\%$ and the sulfur content is virtually unchanged. **Table 4** summarizes these findings. Since the slag-metal reaction is suppressed in the PM treatment, molten steel is relatively uncontaminated by slag. Oxidation losses of aluminum and manganese are small and this process is low in susceptibility to the influence of slag on the bath surface.

Table 4 Change of chemical compositions by the PM process

Mn($\times 10^{-2}\%$)	P ($\times 10^{-3}\%$)	S ($\times 10^{-3}\%$)	N (ppm)	Al ($\times 10^{-3}\%$)
−0.33	0.11	−0.13	0.85	0.9

4.6 Molten Steel Temperature Drop

Figure 17 gives a comparison of the molten steel temperature drop in the PM process and the RH and argon bubbling processes. In the PM process, the temperature drop is about 16°C after a 10-min treatment; this value is the same as in the argon bubbling process. When the same ladle is used, the temperature drop in the RH process is 22°C after 10-min treatment. Therefore, the molten steel heat loss during the PM treatment is about 25 to 30% less than in the RH process. Compared to the RH process, the contact area between molten steel and the refractory is small in the PM process and the exposed area not covered with slag also is small.

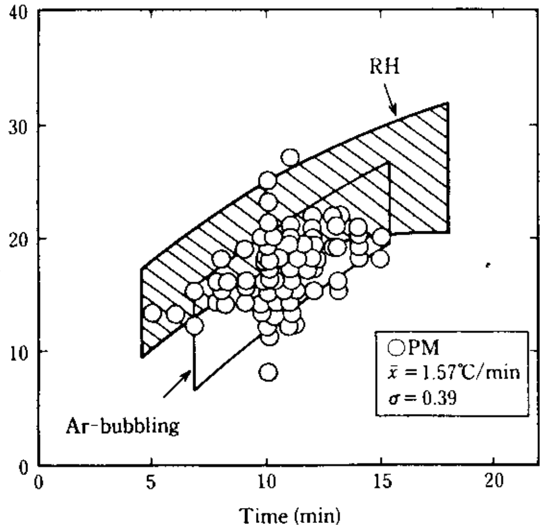


Fig. 17 Drop in temperature during treatment

It may be said therefore that the PM process is a ladle refining process excellent also in terms of molten steel temperature drop.

4.7 Homogeneity of Molten Steel Due to Mixing

Figure 18 shows a comparison of the molten steel temperature drop ΔT and the oxidation loss of aluminum, Δ[Al], which occur between the end of treatment and pouring into the CC tundish for the PM process and the argon bubbling process. In the PM process, ΔT is smaller than in the argon bubbling process by 2°C on average and Δ[Al] is smaller by 0.2×10^{-3}%. In the PM process, stirring of the molten steel in the ladle is better than in the argon bubbling process, and the molten steel is thoroughly mixed at the end of the treatment. Therefore, the subsequent molten steel temperature drop and change in the chemical composition can be considered small.

5 Quality

To show the effect of the PM process on the reduction of large nonmetallic inclusions, an investigation was

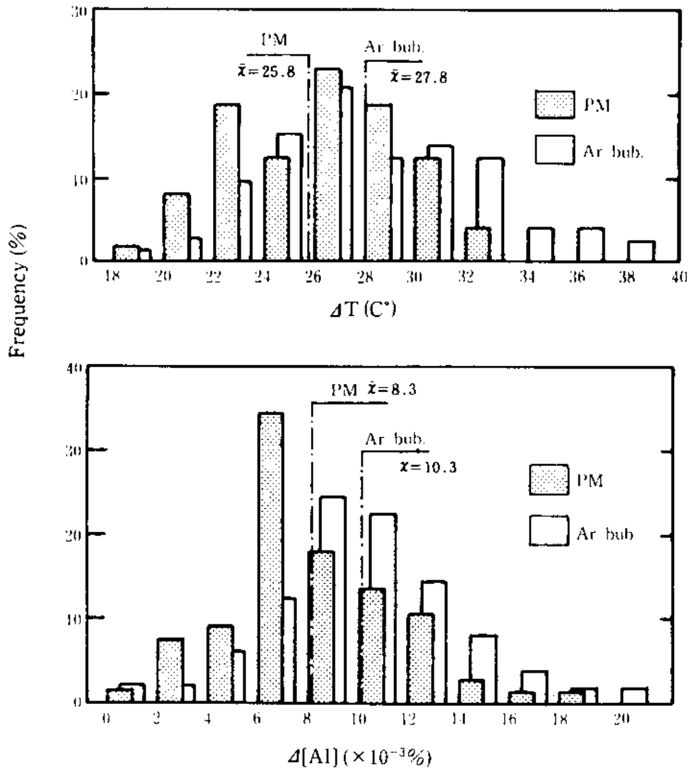


Fig. 18 Decrease of Al content and temperature from the end of treatment to CC-tundish

made into changes in oxide inclusions during treatment, distribution of sulfur spots in slab representing large inclusions, and amounts of large inclusions extracted by the slime method.

5.1 Behavior of Oxide Inclusions during Treatment

An investigation was made into the behavior of inclusions in bomb samples taken during the PM treatment and from the CC tundish. Oxide inclusions only were measured, using QTM (QUANTIMET). The measurement was carried out at 600 magnifications × 60 fields. The steel used was a low-carbon aluminum-killed steel (0.03%Al). Typical examples of results are shown in **Table 5**.

Table 5 Cleanliness* d_T (area of oxide inclusion) (%)

Before treatment	5 min	10 min (end)	tundish of CC
0.086	0.056	0.035	0.027

• Al killed steel

Cleanliness d_{Total} relative to oxide inclusions is as good as 0.027%. Inclusions were initially Al_2O_3-like clusters and changed into fine separate Al_2O_3 particles. No Al_2O_3 clusters are observed in the tundish, and the diameter of the inclusion particles is mostly 5 μm or less.

5.2 Distribution of Large Inclusions in CC Slab

To verify the effect of the PM process on the reduction of large inclusions, the number of sulfur spots, representing large inclusions, was counted on sulfur prints of the cross section of CC slabs for ERW pipe. The results are shown in **Fig. 19**. This figure also contains results obtained from steels subjected to the RH treatment and argon bubbling treatment and continuously cast under virtually identical conditions. The number of sulfur spots in the PM-treated steel is approximately the same as that in the RH-treated steel. Thus, the PM process and the RH process have very similar effects on the reduction of large inclusions.

Figure 20 shows the particle size distribution of large inclusions in a PM-treated steel for ERW pipe, extracted by the slime method, in comparison with that in an RH-treated steel for deep drawing quality steel sheets (DI can class). The maximum particle size of inclusions in the PM-treated steel is 150 μm or less, and the amount extracted is 0.2 mg/10 kg · steel, almost the same as in the RH-treated steel. It is apparent, as a result, that the PM process has almost the same effect on the reduction of large inclusions as the RH process.

5.3 Quality of Products

To determine the effect of the PM process on the improvement of product quality, an investigation was made into the incidence of surface defects (slivers) in cold-rolled steel sheets made from low-carbon aluminum-killed steel and, for ERW pipe made from hot-rolled steel sheets of aluminum-silicon-killed steel, the percent defective as detected by ultrasonic testing. The results are shown in **Table 6**. This table contains, for purposes of comparison, results obtained with steels given argon bubbling treatment and RH treatment and manufactured under the same conditions.

The incidence of slivers in the cold-rolled steel sheet subjected to the PM treatment is about 20% lower than that of the cold-rolled steel sheet subjected to the argon bubbuling treatment. Furthermore, the PM process shows almost the same results as the RH process in terms of the percentage of ERW pipe judged defective due to hook cracks and large inclusions ultrasonic testing. Thus, the PM process was found effective in improving both the cleanliness of molten steel and the quality of products.

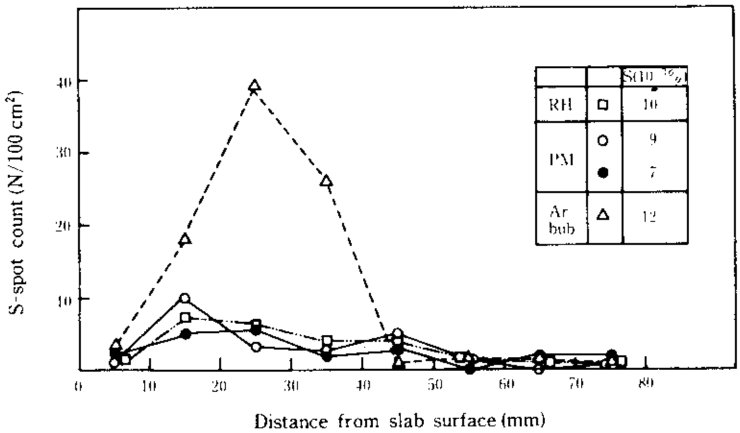


Fig. 19 Distribution of S-spots along the thickness of slab as determined on sulfur print (Al-Si-killed steels for ERW pipe)

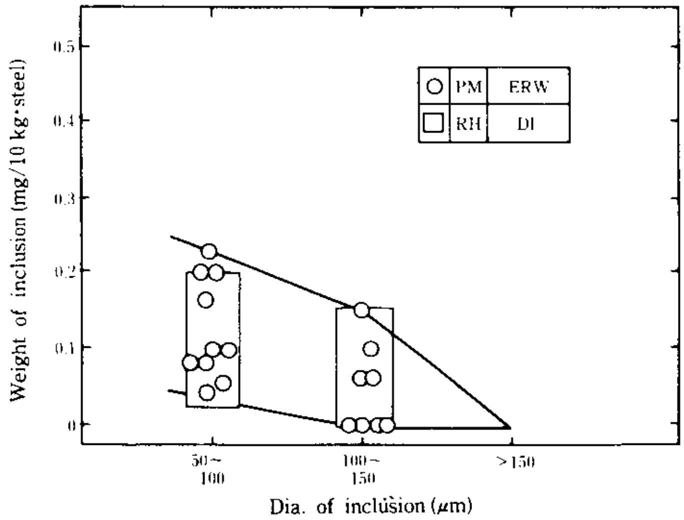


Fig. 20 Amount of large inclusion extracted by the slime method

Table 6 Quality of products (defect index)

Process	PM	RH	Ar-bubbling
Slivers of Al-killed cold sheet	0.8	–	1
Inner defects of ERW pipe (UST)	0.7	1	–

6 Refractories for Cylinder

The cylinder used in the PM process is 600 mm in inside diameter and 3 500 mm in total length. MgO-Cr_2O_3 bricks with excellent wear resistance are used in the area where the molten steel flow is violent. A high-Al_2O_3 castable refractory is used in other parts. The life of the immersed tube, which is extremely susceptible to wear, is more than 100 heats in intermittent operation. The amount of refractory wear in this case is 1 mm/heat or less, no great difference from that with the conventional circulation tube in the RH process.

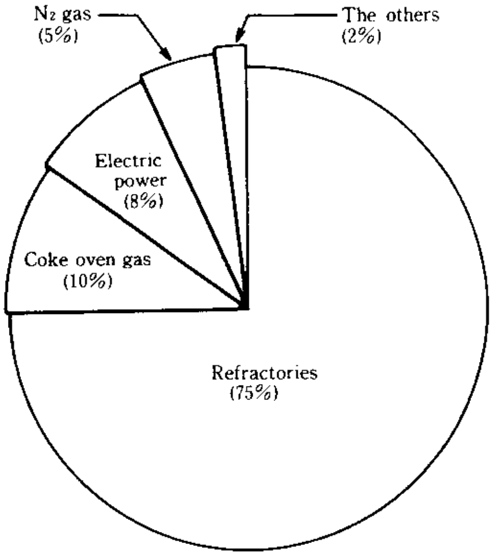


Fig. 21 Constitution of operational cost of PM treatment

7 Treatment and Construction Costs of PM Process

Figure 21 shows the treatment costs of the PM process. Based on test results, the cost calculation was made by assuming a 12 min treatment time.

The cost of refractories accounts for 75% of the total cost, the fuel cost for preheating refractories 10%, and the cost of nitrogen gas for pressurization only 5%. The treatment cost of the PM process is about 1/8 that of RH degassing process of the same scale.

The construction costs of PM equipment are about 10 to 20% that of ordinary RH degassing equipment, although this varies with the conditions of ancillary facilities. Thus, it is apparent that the treatment cost and construction cost of the PM process are low and the process, therefore, can be considered economical.

8 Conclusions

Kawasaki Steel developed the pulsating mixing (PM) process for ladle refining. This PM process is economical and has excellent refining effects. The process is being successfuly used in commercial operation, with the following results:

(1) Time required for uniform mixing
Uniform mixing time is only 100 to 200 sec. This process provides a sufficient stirring force to molten steel, in spite of the simplicity of the equipment.

(2) Deoxidation
The oxygen concentration after treatment is low compared to that of the argon bubbling process and variations are small. The PM process is very effective in improving the cleanliness of molten steel, and is approximately equal to the RH degassing process in this respect.

(3) Alloy addition
The yield of addition of alloys of aluminum, carbon, boron, titanium, etc. is 90% or more. The PM process is equivalent to the RH degassing process in the accuracy of alloying element adjustment and the yield of addition of alloys. In particular, as much as 0.1 kg/t · steel of aluminum can be saved in comparison with aluminum consumption in the argon bubbling process.

(4) Large inclusions
The PM process is very effective in reducing large inclusions. The quality of PM-treated steel products is equivalent to that when the RH degassing treatment has been used.

(5) Molten steel temperature drop
The molten steel temperature drop in the PM process is the same as in the argon bubbling process and is about 25 to 30% smaller than in the RH degassing process.

(6) Contamination by slag
The oxidation loss of manganese and aluminum and amount of phosphorus pick-up due to the presence of slag are small. The PM process is low in susceptibility to the influence of slag on the bath surface.

(7) Operations costs
The cost of refractories accounts for the greater part of the treatment cost. Treatment cost is about 1/8 that with RH degassing equipment of the same scale.

(8) Construction costs
The construction cost is 10 to 20% that of RH degassing equipment because of the simplicity of construction of the equipment.

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