Forming Factors of Blowhole Defect in Continuously-Cast Beam Blank at Dragon Steel

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It is well known that the presence of dissolved [O], [N], [H] in the liquid steel can cause blowholes formation in the continuous casting process. So, gas levels must be kept at a minimum in the steelmaking and continuous casting process. The aim of this work is to investigate the possible sources of these gases including hydrogen, nitrogen and oxygen, focusing on the preparing process that are in contact with the liquid steel during refining and casting. The tundish refractory lining, covering agents, slag and casting powders were analyzed. Effects of chemical composition and gas level on defects formation are also investigated. The results showed that not only the humidity content in those refractories using in tundish preparation is critical, but also improving the oxygen removing efficiency is important as well.

Keywords: Blowhole, Supersaturated precipitation, Continuous casting

1. INTRODUCTION

The appearance of blowholes in the steel occurred at Dragon Steel is required to speedily identify their origins, which were found in some heats near the surface and inside the continuously casting (CC) beam blanks with heavy sections, and are out of acceptable quality. From some reports, the solutes of [O], [N], [H] dissolved into liquid steel exceed the equilibrium solubility of gas and then precipitate along interdendritic liquid during the solidification. Some control methods to suppress blowholes formation are applied. The deoxidising, suppression of secondary oxidation, and reduce adequately the hydrogen pickup of ladle slag and the moisture in the refractory material. Blowholes were found in some heats near the subsurface and inside the beam blank after scarfing and some of them were easily visible to the naked eye, as shown in Fig.1. Table 1 shows the inspection standards for beam blank at Dragon Steel. When the number of blowholes is higher than 100 piece per meter (i.e. class 4&6), production would not allowed to pass. The statistical analysis shows that the defect rate of steel grade A36 is much higher than that of A572.

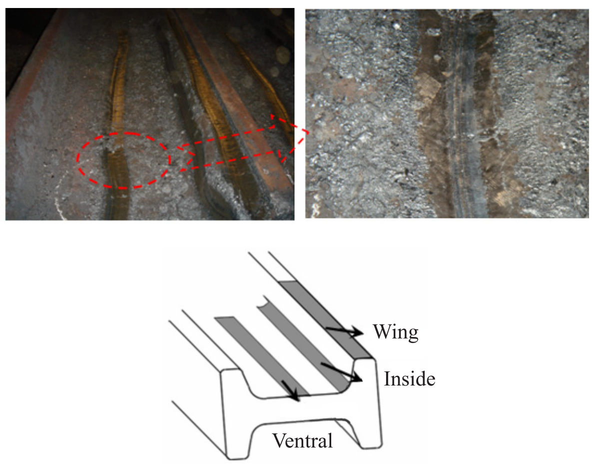

Fig.1. Blowholes formed on at beam blanks are inspected by scarfing.

Table 1 Inspection standards and handling way for beam blank

Class	Blowhole, pc/m	Handling way
1	0-20	Pass
2	21-49	Pass
3	50-99	Allowed for H5X/H6X/H4G
4	100-150	Allowed for small size H42/H32/H35/H27
		Rejected for the 1st heat
6	>151	Rejected

The steelmaking process of beam blank employed in Dragon Steel is shown in Fig.2 First the scrap and sub-materials are charged into an electric arc furnace for melting and steelmaking. While liquid metal is being tapped into the ladle, 80kg aluminum ingots were added for deoxidization. In general, the tapping temperature is maintained to higher than 1610°C for the first heat of the run to prevent the liquid steel from freezing during casting. Then the ladle furnace is applied to adjust the chemical composition, temperature and gas level by adding flux and ferro-alloys. After the ladle refining, ~40kg CaFe wire is also injected to suppress the free oxygen to below 10ppm before pouring. Then the ladle was lifted to the CC machine, where the slide gate is opened to let the molten steel flow into the tundish and mold in the open atmosphere. Sometimes oxygen is blow into tundish to raise the temperature if the temperature of molten steel becomes too low.

The objectives of this research are to study the influence of the process parameters on the formation of the blowholes in continuously cast beam blanks, the mechanism by which these steel grades and degassing procedure, and to identify possible ways in which defect-free continuously cast beam blanks can be produced.

2. LITERATURE SURVEY

Previous studies show that blowholes appear by increased content of gases nitrogen, hydrogen and carbon monoxide. When the total gas pressure of these enriched solutes in interdendritic liquid exceeds the local external pressure, gas bubbles are generated, resulting in expulsion of the interdendritic liquid into the neighboring regions, and hence the blowholes or pinholes are formed during solidification[1]. This statement is summarized by following equation.

$$P_{Bubble} = P_{H_2} + P_{CO} + P_{N_2} \geq \quad P_s + P_f + \frac{2\sigma}{r}(\sim 0.03atm) \quad \cdots\cdots (1)$$

Where

P_s= atmospheric pressure on the surface of liquid steel in the mold

P_f=ferrostatic pressure at the location of blowholes

σ =surface tension of liquid steel in contact with the gas bubble of radius r

The solubilities of [N], [H] and [O] in molten steel at 1550°C are about 25.6ppm, 457ppm, 0.21%[1,2]. During the cooling of liquid metal, the soluble amount decreases gradually. However, there is a sudden drop of solubility at the phase change from liquid to solid, as shown in Fig.3 The subsurface blowhole formation in continuous casting will occur in the early stage of the solidification. An average of 1.05~1.1atm is taken as the critical total gas pressure for the onset of the subsurface blowhole formation. It is located at a short distance below the meniscus where the total pressure is only slightly above atmosphere in continuous casting. The critical solubility of hydrogen drops to 6~10ppm and which for nitrogen is to below 90ppm.

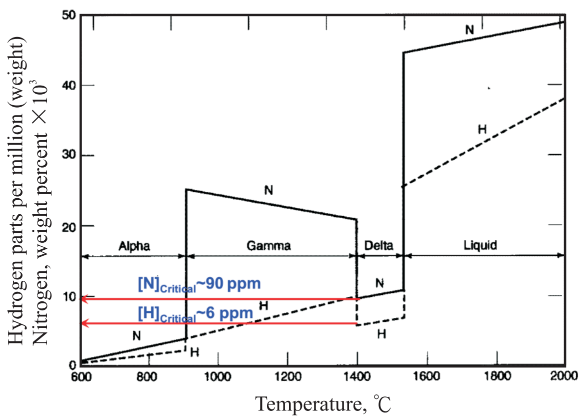

Fig.3. Solubility of nitrogen and hydrogen in iron and steel.

Some works of investigation on the formation mechanism of this type defect shows that the critical solution content of [H], [O] and [N] is varied with composition. The solubility of [H] increases with [Si] and [Mn] addition, but decrease with carbon. In order to investigate the effect of solutes in molten steel on the built up of gas pressure, the behavior of gases such as O_2, N_2, CO dissolved in liquid and solid iron was investigated. For ideal solutions, the concentration is directly proportional to the equilibrium gas partial pressure, which is known as the Sievert's law. The analytical result is shown in Fig.4.

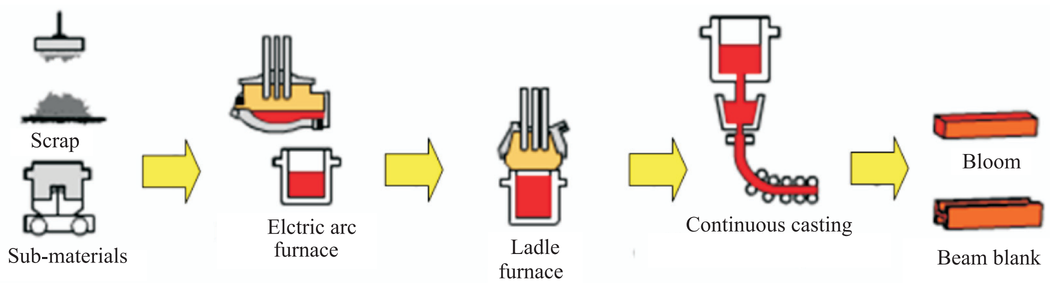

Fig.2. Steelmaking process of beam blanks at Dragon Steel.

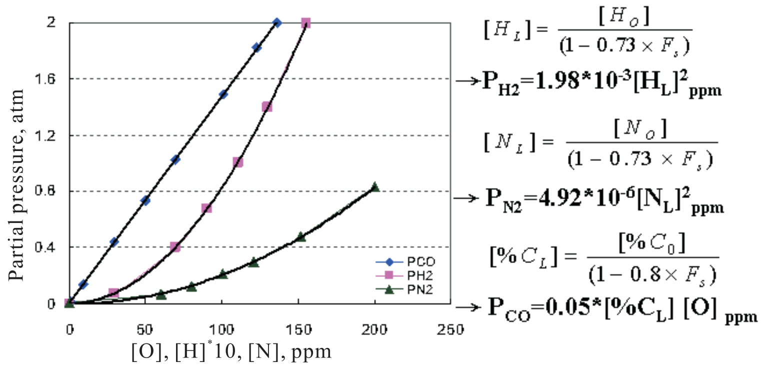

Fig.4. Gas partial pressure vs. solute dissolved in steel at 1500°C.

3. EXPERIMENTAL METHOD

3.1 Blowholes observation and gas analysis

Figure 5 shows the photograph of radiography test of blowholes formed at the wing plate of beam blanks. Severe subsurface blowholes extend from subsurface and penetrate along the interdendritic region. Some of them are 1.5~2cm in length. The blowholes were observed in the subsurface of CC beam blanks, while sometimes blowholes were visible after scarfing. The presence of blowholes in solidified CC products is over the full length of each strand. And the cast strand in the first heat has more blowholes than the intermediate heats.

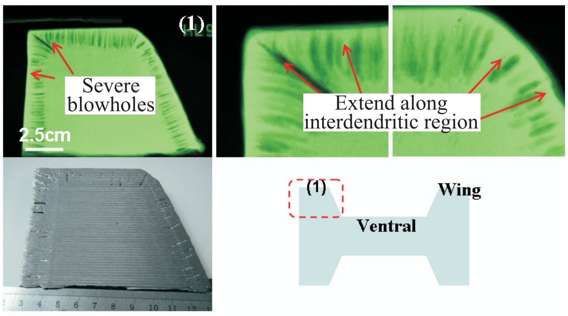

Fig.5. Image of the subsurface blowholes under RT.

A number of investigations have been made to identify gas composition to determine the gas sources of blowholes (3~5). In this study, steel samples were drilled under water and the evolved gas was collected into a test tube. Then the gas sample was injected into a sample bag with carrier gas of helium in a dilute ration of 1:1000 to form a gas steam. The test sample then is injected to a gas chromograph (GC) instrument which transports the sample into a separate tube and various components are separated. The detector measures the quantity of the components by a standard sample with known concentration also injected into the instrument. The standard sample peak retention time and area are compared to the test sample to calculate the concentration. The analysis results are shown in Table 2.

The result of the analysis shows that the main components of the gas are H_2(66.85%), O_2(19.52%) with N_2(5.6%), Ar(1.7%), CH_4(6.54%), and CO_2(0.32%), CO(0.22%) is also included as a minor component. The resultant analysis is not consistent with the theoretical values. The reason for this inconsistency is attributed to the contamination of the gas with atmospheric air during the procedure to remove gas sample from the collecting medium to a gas analyzer. The major components of the blowhole gas is H_2(90.74%), and the minor are CH_4(8.87%), CO_2(0.37%), CO(0.22%) after modifying the effect of background gas composition.

Table 2 Gas composition

		H_2	Ar	O_2	N_2	CH_4	CO	CO_2
Sample	(ppm)	347860	8683	101600	26433	34020	89	1683
	%	66.9	1.7	19.52	5.1	6.5	0.22	0.32
Background	(ppm)	0	23118	236562	65787	0	0	654
	%	0.00%	7.1	72.54	20.2	0.00	0.00	0.20
Actural bas bubble	(ppm)	347860	-606	0	-1822	340200	89	1402
	%	90.7	-0.2	0	-0.5	8.9	0.22	0.37
At 1500°C while blowholes formation	(ppm)	351640	-1246	0	-1821	0	30329	333
	%	92					7.9	0.09

The gas bubble composition is performed by GC at room temperature. In order to identify the actual gas composition while blowholes form during solidification, thermodynamic activities of gas reaction are applied to predict gas reaction between them in the beam blank continuous casting(1). This analysis is summarized and shown that CO_2 and CH_4 observed as GC data come from the following reaction during cooling:

$$2H_2(g)+2CO \rightarrow CH_{4(g)}+CO_{2(g)} \quad (2)$$

$$\Delta G=\Delta H-T\Delta S=-257500+271.8T=-RTLnK$$
$$=-19.14LogK$$

$$T=1773K; \quad K=\frac{P_{CH_4}\times P_{CO_2}}{(P_{H_2})^2\times(P_{CO})^2}=2.44\times10^{-7}$$

assume P_{H2}, P_{CO},～1 atm,
then P_{CH4} <<1 atm(without CH_4)

$$T=773K; \quad K=\frac{P_{CH_4}\times P_{CO_2}}{(P_{H_2})^2\times(P_{CO})^2}=1598.243$$

P_{H2}, P_{CO}, P_{CO2}, $P_{CH4} \geqq 1$ atm(CH_4)

The calculations reveal the real gas composition where CH_4 and CO_2 do not exist at the stage of blowhole formation in the interdendritic liquid at about 90% of solidification. Therefore, the major components of blowhole are H_2(92%), CO(7.9%) and CO_2(0.09%). The high amounts of [H] and [O] dissolved in the liquid steel are the major contributors to blowhole formation.

3.2 Process analysis of steelmaking

Detail data statistics has shown that the appearance of blowholes may be connected to certain factors. Figure 6 shows the effect of the number of heat runs on the defect rate. By increased number of heats, the number rejected CC blooms decrease due to the decline of blowholes rate. The most severe blowhole problem generally occurs at the first heat. It shows obviously that the presence of such phenomenon is connected to some operation which varies with the number of heat runs: the preheating of the tundish, steel temperature in ladle furnace (LF), or ferro-alloy/flux additions.

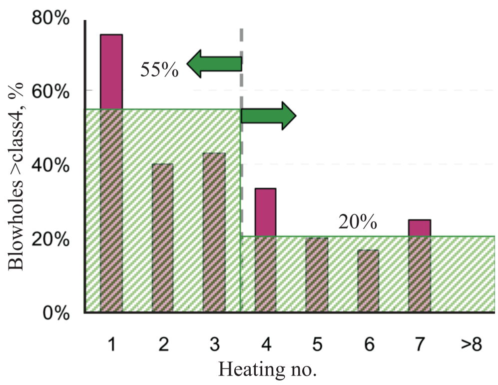

Fig.6. Effect of heat number on defect rate.

In the practices of steelmaking at Dragon Steel, some operations, such as raising the tapping temperature of the ladle furnace, and the blowing oxygen into tundish to increasing tundish temperature, would be adapted at the first heat of run to prevent the liquid frozen. Such operations would damage severely the gas level control in molten steel. Figure 7 shows the effect of tapping temperature on the blowhole. A higher tapping temperature increases gas solubility and results in more [N], and [O] being dissolved into liquid thereby promoting blowholes formation. Figure 8 shows the [N], [H], and [O] contents in the steel, measured in the stage of the ladle and tundish. The graphics compares the different pickups of the dissolved gases between the ladle and the tundish. In statistical average, The [H] pick up rise from 7.6 to 10.3ppm; [O] rises from 15.2 to 21.3ppm, and [N] increases 20.3ppm in statistical average.

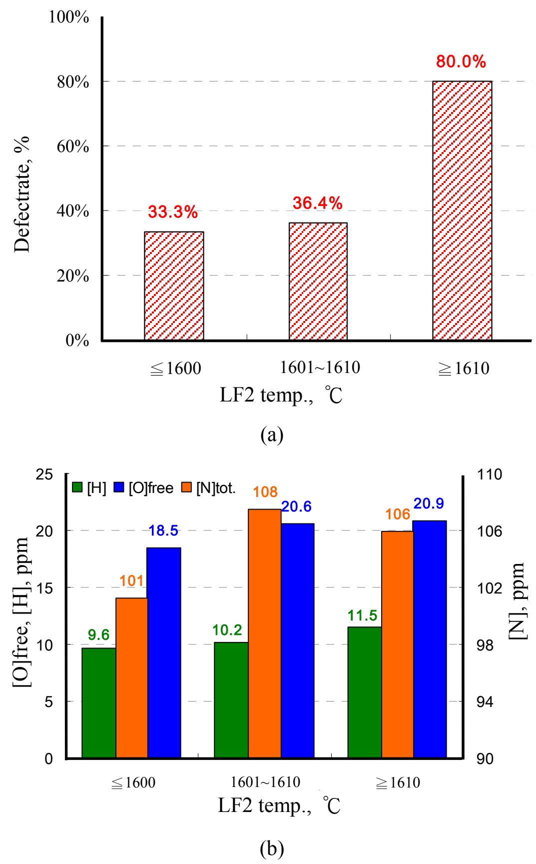

Fig.7. (a) Effect of tapping temperature on defect rate, (b) higher trapping temperature results in higher [N], [H], [O].

In the practices of ladle furnace refinging at Dragon Steel, the molten steel is often tapped with some aluminum ingot of 80kg addition. With the ladle refining the meltis deoxidized is to below 20ppm. Noting that the solutibility of hydrogen increases with enhenced deoxidizing, it is suggested that ferro-alloys or ladle slag is probably the contributor to the hydrogen pickup. The analysis reveals that hydrogen pickup is due to those addition is only 0.8ppm in an average value, which is much less than that of 2.7ppm during the melt being transported form ladle to tundish. Therefore, it can be inferred that the tundish is the major hydrogen source, and contribute more hydrogen pickup compared to that in the ladle. There is a similar tendency for [N] and [O], but the pickup of [N], [O] is due to opening pouring, which is a minor factor to deteriorate blowholes.

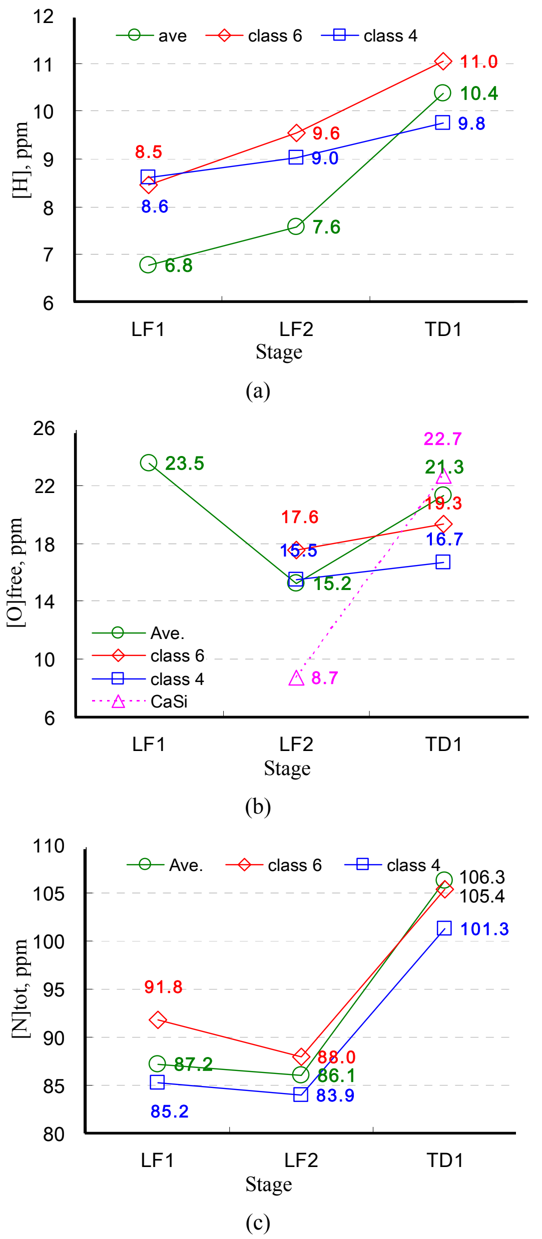

Fig.8. (a) [H], (b) $[O]_{free}$, and (c)$[N]_{tot.}$ variations at different stages.

Figure 9 shows the statistical analysis of beam blank quality after scarfing and reveals that the defect rate is the function of hydrogen content in molten steel and no connection was found between the blowholes and the content of oxygen and nitrogen in the tundish. The blowholes defect deteriorates further when [H] in the tundish is higher than 10ppm. This critical phenomenon is also confirmed by Fig.2.

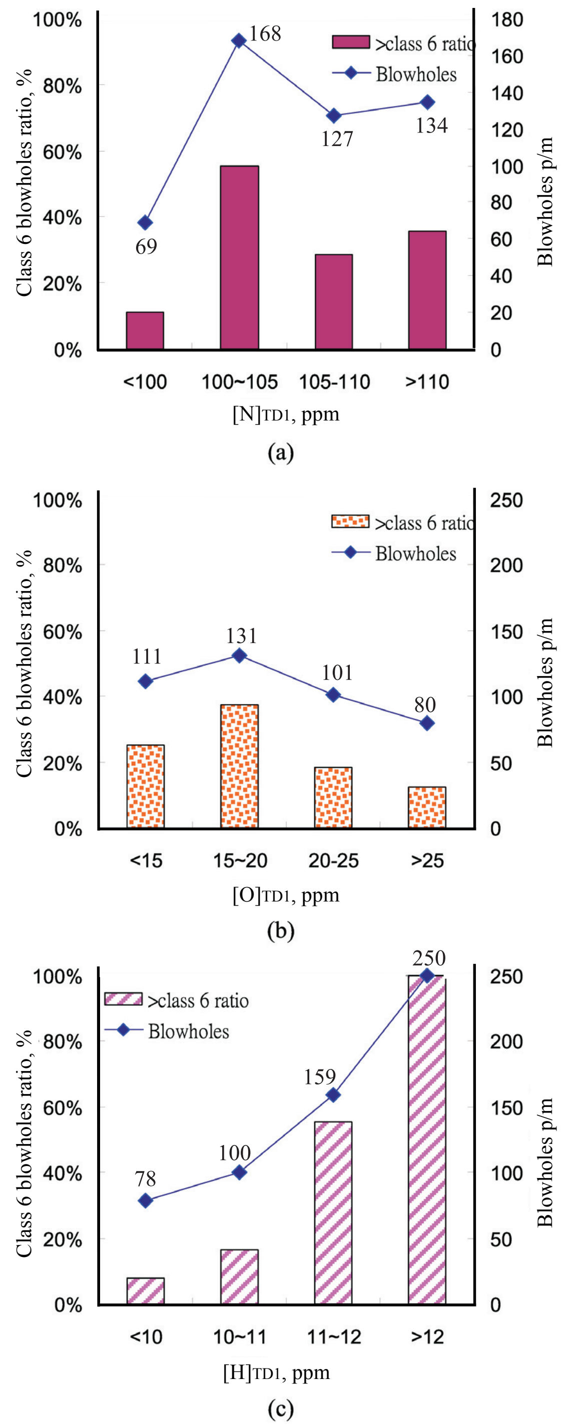

Fig.9. Effect of gas contents on blowhole formation: (a) $[N]_{TD1}$, (b) $[O]_{TD1}$, and (c) $[H]_{TD1}$.

The gas partial pressures are calculated for the solute enriched concentrations using the relationship in Fig.2. Figure 10 shows that a higher total gas pressure results in a greater blowholes formation. The blowhole defects rise to higher than 50% when the total gas pressure is higher than 1.3atm. The initial blowholes occur at a total gas presure of near to 1.04atm, which is taken as the critical total gas pressure for the onset of the initial subsurface blowhole formation in the continuous casting of beam blank. From the previous observation from an RT photograph the of defect sample, it can be seen that the blowhole initiate in the subsurface (0.2~0.5cm below the surface), where there is a solidification front 5~10cm below mold level, and the total gas pressure reaches to 1.042atm (ferrostatic pressure P_f~0.014atm; surface tension σ~0.03atm).

The influence of gas partial pressure on the most severe defect (i.e. class 6) is shown in Fig.11. With a higher [H] content, the partial pressure increases and results in the blowholes defecting to deteriorate further, but there is no aparent effect for the other solutes of [N], and [O]. This finding implied that hydrogen in the steel is the major contributor to cause a build up of gas pressure to promote gas bubble formation. Figure 12 shows the effect of gas partial of hydrogen content on the blowholes formation from statistical analysis. Taking a 1.35atm as the critical gas pressure for the onset of blowhole formation, the critical hydrogen content is estimated at 9.7ppm as the inspection value. If [H] is higher than 9.7ppm, there will be a build up of more than 1.35atm for the total gas pressure, and which would result in the development of severe defects.

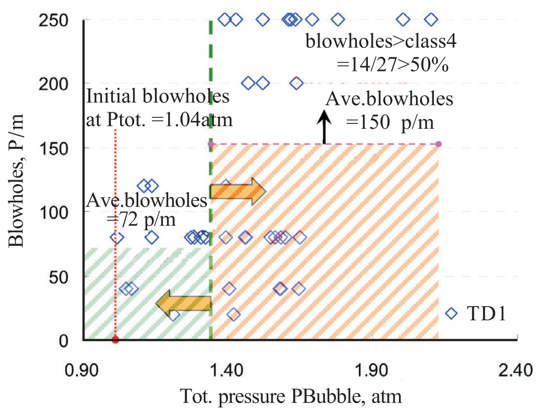

Fig.10. Relationship between total gas pressure and blowholes.

4. COUNTERMEASURES TO BLOWHOLES FORMATION

Considering all the analyzed materials which would contact/react with liquid steel, as shown in Table 3, the major source of moisture is CaO addition and the sealing material used in tundish repair [6,7]. CaO added in to an EAF and ladle for steel refining result in a 0.8ppm [H] pickup, and the major contributor for [H] pickup is the tundish. From the previous analysis, hydrogen pickup in the tundish is the major contributor to blowhole formation. Moisture from the tundish sealing gel penetrating into liquid steel is the major source of hydrogen.

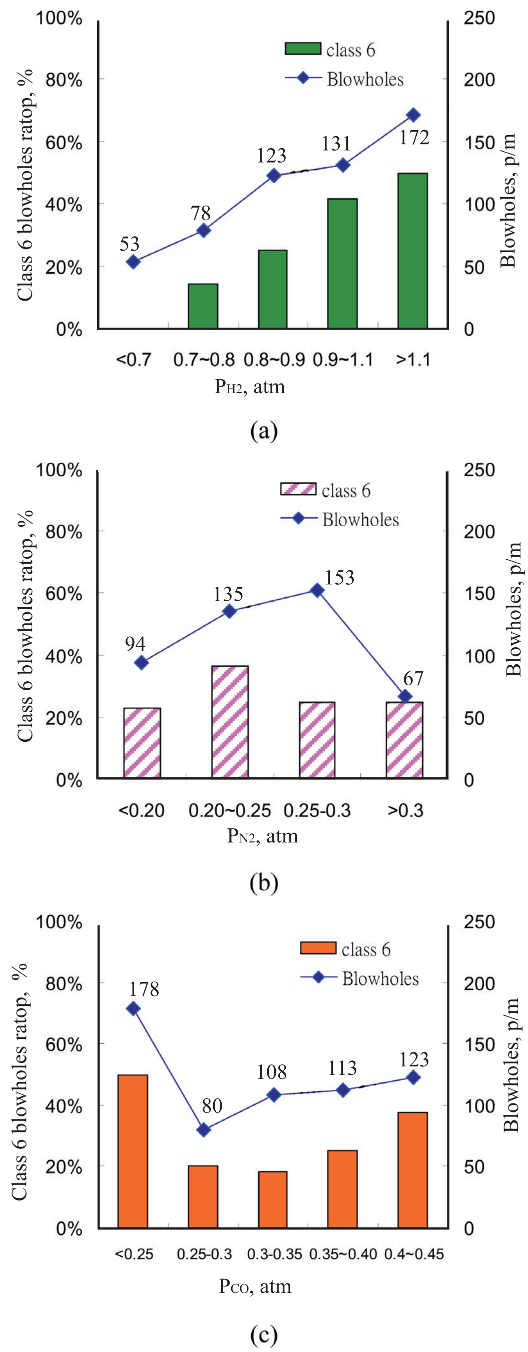

Fig.11. Relationship between defect rates of class 6 and the gas partial pressure, for (a) P_{H2}, (b)P_{N2}, and (c)P_{CO}.

Table 3 Moisture content measurement for all materials which would contact / react with liquid steel

Materials	Moisture content, wt%
Cover	<0.05%
Mold flux	<0.04%
CaO(CaOH)	0.5-2% depending on drying time
Tundish plate	<0.045%
Sealing gel	1-8% depending on drying time
Sand	<0.05%

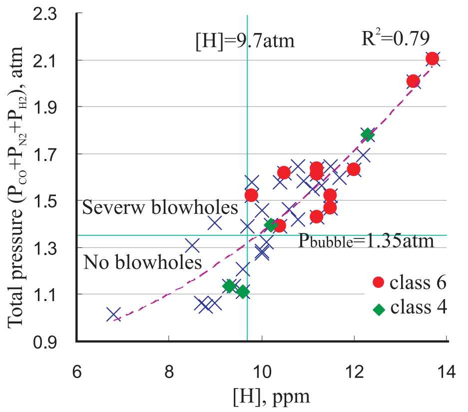

Fig. 12. Effect of [H]content in liquid steel on total gas pressure and blowhole formation.

The degree of hydrogen pickup strongly depends on the partial pressure of water vapor (relative humidity) in the atmosphere. The pickup is further more in the tundish was assembled using sealing gel and came into operational run after natural drying for just 24-36hr. The sealing gel is made by mixing 25kg seal powder and 12.5kg water for a tundish assembly. A nature drying test of the sealing gel was performed under different drying conditions. For the first sample made under a higher relative humidity conditions (RH~100% on a rainy day), the drying time to remove moisture to below 3% was much longer than that at lower RH conditions. The results showed that the natural drying time was insufficient for the complete removal of the structural water and resulted a [H] pickup of 1~2.5ppm.

Some control methods and improvements have been deduced from the above discussions. The control of the solutes dissolved in liquid steel in ladle refining, such as $[N]_{tot.}$< 80ppm, $[O]_{free}$< 15ppm and increasing tundish drying time. With these countermeasures implemented in the steelmaking and casting, the defects have shown significant improvement. The defect rate has shown a dramatic reduction from > 10% to<1%. Consequently, few defects have been detected in the quality data[8].

5. CONCLUSIONS

(1)The blowhole formation is mainly attributed to hydrogen pickup in the tundish, which results in a build up of total gas pressure to exceed the critical gas pressure in the early stage of the solidification.

(2)The main source of hydrogen pickup is due to sealing gel in tundish refractory lining. The drying time is too short to remove sufficient moisture from the sealing gel, which cause more hydrogen penetrating into the molten steel.

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