Laminar Barrier Inerting for Induction Melting

S. K. Sharma
Development Associate, Linde Division, Union Carbide Industrial Gases Inc.
Tarrytown Technical Center, Tarrytown, NY 10591

M. S. Nowotarski
Development Associate, Linde Division, Union Carbide Industrial Gases, Inc.
Tarrytown Technical Center, Tarrytown, NY 10591

Presented at the Investment Casting Institute's INcast GOLD RUSH 189, 37th Annual Technical Meeting and Mini Show, Los Angeles, CA, October 15-18th, 1989.

ABSTRACT

A new method called Laminar Barrier Inerting (LBI) has been developed by the Linde Division of Union Carbide Industrial Gases Inc. (UCIG) for providing inert atmospheres in open ended enclosures. This patented technology was used at an investment foundry to prevent atmospheric contamination during induction furnace melting by providing a gas barrier across the furnace opening. LBI is able to maintain oxygen levels below 1% during the entire cycle of charging, melting, and final composition and temperature adjustments. The present paper describes the results of using LBI on induction furnace melting to decrease oxidation and slag formation thereby improving casting quality and yield while decreasing casting rejects.

SUMMARY AND CONCLUSIONS

Laminar Barrier Inerting (LBI) of open ended enclosures which has been recently developed by the Linde Division of Union Carbide Industrial Gases, Inc., was tested for inerting 1000-lb induction melting furnaces at an investment casting foundry. Several grades of stainless steels, copper, nickel and cobalt base alloys and low alloy carbon steels were melted in approximately seventy 1000-lb heats using this inerting technology. Nitrogen and argon were used as the inerting and purging gases during the trial. Extensive sampling and data collection was done to determine head space O_2 and N_2, bath oxygen, nitrogen and hydrogen contents, and casting quality and cost improvements. The results showed:

- The LBI process and equipment performed very well maintaining desired oxygen and nitrogen levels in the head space. Depending on the gas flow rate, the head space oxygen content was varied between 0.5 to 1.5%, and nitrogen content between 15 to 30%.
- The inerting equipment allows complete furnace visibility and accessibility and is able to maintain the above levels of oxygen and nitrogen during routine furnace charging and sampling.
- Oxygen in the melt was 30 to 60% lower in LBI heats than in normal air-melted heats.
- Nitrogen in the melt for LBI heats was maintained at the same or somewhat lower levels than that of the normal heats. Nitrogen contents can be lowered further by increasing the ratio of argon to nitrogen.

- Hydrogen content in LBI heats was 40 to 75% lower than the air-melted heats. The atmosphere above the melt aided in hydrogen degassing and prevented H_2 pick-up from the atmosphere.

- Slag formation and alloy oxidation were considerably reduced in the LBI heats resulting in reduced slag build up, improved lining life and decreased alloying additions.

- Because of decreased O_2, H_2, slag and oxide inclusion content in the metal, the casting quality for LBI heats was improved. The overall rejection rates for different alloy grades in LBI heats were significantly lower than those for standard heats.

INTRODUCTION

A new method called Laminar Barrier Inerting (LBI) has been developed by the Linde Div. of Union Carbide Industrial Gases Inc. (UCIG) for providing inert atmospheres in open ended enclosures. This patented technology has been used to prevent atmospheric contamination during induction furnace melting.

The present paper reviews basic operating principles and describes the results of applying the LBI process to induction furnace melting to decrease oxygen, nitrogen and hydrogen pick-up, oxidation losses and slag formation, thereby improving casting quality and reject rates. LBI was able to maintain oxygen levels in the furnace head space below 1% during the entire cycle of charging, melting, and final composition and temperature adjustments. A distinct advantage of the LBI process was its ability to maintain low oxygen levels in the furnace without blocking or restricting access to the furnace mouth.

Operating Principles of Laminar Barrier Inerting (LBI)

The Linde Division of Union Carbide Industrial Gases is a leader in inerting technologies, particularly gas curtains. Gas curtains usually consist of one or more pipes with a row of holes which blow gas across an opening. The curtain flow traps a purge gas and reduces air infiltration(l). A major limitation of gas-curtains of this type is that the flows are turbulent. This turbulence can often aspirate more air into an opening than can be excluded.

Laminar Barrier Inerting (LBI) is a way to form a gas curtain which will exclude air with minimal turbulence. The basic idea is illustrated in Figure 1. An induction furnace is shown with an LBI element on two sides Of the top of the opening. Each LBI element consists of a gas inlet, a plenum chamber and a porous face. The curtain gas is introduced into the plenum and flows out through the porous face as an evenly distributed, wide laminar flow of gas. Since the flow is wide and laminar, no air can mix across it and into the chamber below. Solid objects, however, can easily pass through the laminar barrier. The result is that visual and physical access is maintained to the chamber below, but air is excluded.

The wide laminar flows of gas from each LBI element meet at the center of the opening and then bend up and away. This forms a plume which has oxygen levels in the middle to low percent range.

No separate purge flow is required with laminar barrier inertingi The barrier gas flowing across the opening sweeps out the air in the chamber. Purge flows may be used either to sweep unwanted atmosphere more rapidly out of the chamber or to maintain a purge atmosphere different in composition from the LBI gas. In the present tests, for example, an argon purge with nitrogen barrier gas was used for nitrogen sensitive alloys. A nitrogen barrier gas alone is adequate for alloy grades for which the associated nitrogen pickup can be tolerated.

The performance of laminar barriers has been described quantitatively. The expected oxygen level inside a chamber versus gas barrier flow can be calculated given operating parameters such as the opening size, gas composition, melt temperature and laminar barrier dimensions. It is beyond the scope of this paper to discuss this model in detail, but most aspects are presented in US patent 4,823,680(2). An illustration of the model is shown in Figure 2.

Figure 2 is a plot of the oxygen level measured in a laboratory furnace (log scale) versus laminar barrier flow rate (dimensionless units). The expected performance based on the model is also shown. At low barrier flows (less than 0.3), the barrier essentially has no effect. There is not enough momentum in the gas for it to flow across the opening. At higher flows, however, the barrier gas covers the opening and the oxygen level drops rapidly. over a flow range of 0.3 to 0.6, the oxygen level drops by 3 orders of magnitude. Eventually, as the flow is increased, the oxygen level drops to a low limit, in this case 0.02% or 200 ppm. This low limit is usually caused by miscellaneous leaks. The tighter the furnace, the lower the ultimate oxygen level that can be achieved.

Laminar barriers have been used to inert molten metal bath surfaces. The barriers are placed directly on the edge of the bath and blow across. This is essentially a no leak situation and oxygen levels as low as 1 ppm have been readily obtained at the bath surface. These very low oxygen levels have resulted in the invention and commercialization of a fluxless dip brazing, galvanizing and electronic soldering processes(3).

No upper limit has yet been found to the size of opening that can be inerted with laminar gas barriers. Sixteen inch diameter openings have been readily inerted. Tests are currently being arranged for inerting a four ft diameter opening on an induction furnace.

EXPERIMENTAL PROGRAM

The test program was conducted on a 1000-lb commercial induction furnace at an investment foundry. The objective was to use LBI on regularly scheduled production heats and evaluate its effects on shop/furnace operations, and product quality. The product mix consists of precision investment castings of several grades of stainless steels, low-alloy carbon steels, nickel and cobalt base alloys. Standard practice at this foundry, with the exception of a few grades, is air-melting in the induction furnace without a cover. During the test program, LBI elements were installed on the furnace, and all heats were made under inert conditions. The inerted heat castings were allowed the same routine handling procedures as those from regular air-melted production. The following grades were inerted during the test program: CF-8M, CK-20, 17-4PH, Ni-base, cobalt-base alloys, 4140, 8620, 86SA, carbon steels, and monels. Table 1 lists nominal chemistries for these alloys. Approximately 70 heats (35 tons) were produced with LBI. Data on normal air-melted heats were also obtained for comparison.

Nitrogen was used as the inerting gas along with a properly designed purge flow of argon gas. With this combination it was possible to keep nitrogen content of the melt at the same or somewhat lower level than those for air-melted heats.

Procedure

The normal procedure for revert charging, melting, tapping and temperature and composition adjustment was followed for inerted heats. Furnace inerting did not affect any segment of shop operation. Typically, the furnace was charged with revert, and the inerting and purging gas flows were turned on along with the electric power. Nitrogen and argon flow rates were controlled to give desired nitrogen and oxygen levels in the head space above the bath. Oxygen and nitrogen concentration in the head space were monitored throughout the heat.

After the revert was completely melted, the metal was held in the furnace for chemistry and temperature adjustments. Once the aim chemistry and temperatures were obtained, the heat was tapped into a ladle for casting. Throughout the charging, melting and holding period, the desired inerting and purging gas flow rates were maintained. The following measurements and bath samples were taken:

- Head space gases sampled throughout the heat for oxygen and nitrogen contents.
- Metal samples at melt down and tap for oxygen, nitrogen and hydrogen analysis.
- Slag samples for oxidation losses.
- Bath temperature measurements.

The flow rates of nitrogen and argon were varied to determine their effects on head space oxygen and nitrogen levels, and bath nitrogen content. Additionally, data on casting rejection rate were obtained.

RESULTS AND DISCUSSION

Headspace Oxygen and Nitrogen Contents

The oxygen content of the head space is a function of the barrier gas flow rate through the LBI'elements (diffusers). As explained earlier (Fig. 2), the higher the inerting flow, the lower the oxygen content. The nitrogen content in the headspace is controlled by the flow rate of argon purge gas. As an example of the barrier and purge flow rates, about 3400 SCFH of N_2 and 2600 SCFH of Ar were used to provide 0.5 to 1% O_2 and 25 to 30% N_2 in the head space.

Depending on the specific argon and nitrogen flow rates used, the oxygen content in the head space was varied between 0.3 to 1.5%, and the nitrogen content was in the range of 12 to 30%. This compares with headspace oxygen of 21% in air-melted heats. The headspace O_2 and N_2 levels were continuously maintained at a given level throughout the entire heat and were not significantly affected by the presence and movement of revert, bath sampling and temperature measurement probes, or alloy additions. O_2 and N_2 levels were also unaffected by furnace tilting during tapping. The furnace mouth was completely and continually accessible to furnace operators for routine operations during the heat and provided full visibility of the furnace contents at all times.

Melt Gas Content

Metal samples were taken at melt down and at tap to determine the effect of inerting on the oxygen, nitrogen and hydrogen contents of the bath. As will be shown in the following discussion of results, the inert barrier successfully provided significantly lower oxygen and hydrogen contents of the bath while keeping nitrogen at the same or lower levels than those of airmelted heats. Tables 2, 3 and 4 show the oxygen, nitrogen and hydrogen concentration in the melt for several different grades of steels as well as nickel, cobalt base alloys.

Oxygen

The total oxygen levels for the inerted heats ranged from 45 ppm to 170 ppm, depending on grade as compared to 75 ppm to 310 ppm for air melted heats of the same grades (Table 2). Thus, LBI lowered the oxygen concentration in the melt by 30 to 60% compared to standard air melting. The reduction in bath oxygen was about 10% for the Ni-base grade. Since the recycling of revert scrap is often limited by the increasing oxygen and nitrogen contents, LBI should allow a higher percentage of returns to be used in such cases.

Nitrogen

Since nitrogen was used as the barrier gas, argon was used as a purge gas to minimize or eliminate pick-up of nitrogen by the melt. The aim was to optimize gas flow rates to achieve bath nitrogen contents which were the same or lower than those of air melted heats. Table 3 lists nitrogen contents in the melt for various grades of stainless steels, carbon steels and nickel and cobalt base alloys and shows that this objective was achieved. The nitrogen contents for all of these alloys were within specification. Use of additional argon purge gas or substitution of argon for nitrogen as the barrier gas would result in a further lowering of nitrogen contents.

Hydrogen

LBI also provided significant reduction in hydrogen contents as shown in Table 4. The inert gas barrier reduced melt contact with atmospheric water vapor resulting in less pick-up of hydrogen and actually provided a significant amount of hydrogen removal. The constant exposure of newly created bare metal surface to an atmosphere with low hydrogen partial pressure is believed to be responsible for this effect.

The Ni-Cu alloy (monel) is quite susceptible to hydrogen pick up leading to reduced casting surface quality. The standard practice is to bubble argon through the melt for hydrogen removal. The air melted monel grade showed 3.27 ppm H_2 before and 2.7 ppm after argon degassing resulting in 17.4% hydrogen removal. For the LBI heat, the hydrogen before degassing was 2.00 ppm. and 1.18 ppm after degassing resulting in 41.0% hydrogen removal during degassing. This shows that LBI not only reduced the initial and final hydrogen levels by -39% to 56% but also increased the efficiency of argon degassing (41% for LBI vs 17.4% for air-melted). Similarly for stainless grade 17-4 PH and cobalt base alloy the final hydrogen contents are 1.55 and 2.40 ppm which were about 75% lower than those found in air-melted heats.

These results show that LBI provides a 40 to 75% reduction in hydrogen content for various grades. This should improve casting surface and internal quality due to a reduction in porosity.

Slag Formation and Alloy Oxidation

Another advantage of LBI over the air-melted heats was a considerable reduction in bath reoxidation. During normal air melting, slag and scum form on the bath due to the oxidation of various elements in combination with furnace lining wear and non-metallic materials in the scrap. Though most of the slag is skimmed off prior to tapping, some slag does carry over to the casting. Entrapment of slag and oxide inclusions in the casting results in poor casting quality. In addition, the slag builds up on the furnace and ladle walls resulting in lower lining life and additional maintenance expense.

Figures 3 and 4 illustrate the difference in amount of slag formed in air-melted and LBI heats. In general, the air melted heats required 5 to 6 slag-skimming (deslagging) operations as opposed to one to three such operations for LBI heats. The picture in Fig. 3 shows the presence of heavy slag on the bath of an air-melted heat as compared to the photograph of an LBI heat in Figure 4 which shows only a light slag layer on the bath. Furnace operators were impressed with this result as the LBI melt required less deslagging and generally cleaner, slag-free metal was obtained for casting. We estimate the amount Of slag in LBI heats was about 50 to 70% less than in the standard air melted heats. This should improve the casting quality and decrease rejection rates by lowering the incidence of slag and inclusion entrapment.

Alloy Oxidation

Slag samples were collected and analyzed for several grades Of steels for air-melted and LBI heats. Air-melted slags contained a higher percentage of chromium and manganese oxides.

Table 5 shows Cr_2O_3, Mno and FeO in slag from CF-8M, CK-20 and low alloy carbon steels are about 50 to 80% lower for inerted heats compared to air-melied heats.

Chromium and manganese oxides in the slag are generated by oxidation of Cr and Mn in the melt which results in fade of these elements and increased alloy additions. The LBI heats not only had lower Cr_2O_3 and MnO contents in slag but also had greatly reduced slag weight resulting in lower amount of Cr and Mn oxidation from the melt. This translates into significantly lower loss of alloying elements and therefore decreased additions to the melt in LBI heats than the air-melted heats. An estimate of the impact on Cr and Mn additions in CF-8M grades shows savings of about 5 lb Cr and 2.5 lb Mn per heat.

Furnace Lining Wear

In the present tests a sintered MgO lining was used. It was observed that the erosion of this furnace lining was markedly reduced during LBI tests due to the reduction in the amount of slag as well as FeO, MnO and Cr_2O_3 contents of the slag. Slag and metal skull on the furnace and ladle linings was considerably reduced during the trial, thus requiring a little or no maintenance after the heat. After 50 heats, the furnace lining showed minimal erosion and required only minor patching compared to furnace repairs that are required after every 10 to 15 heats for an air-melt practice. While enough heats were not made during the trial to actually measure the increase in furnace lining life, these observations clearly show that benefits of reduced maintenance and extended furnace lining life are realized.

Casting Quality and Reject Rates

The castings were subjected to the usual quality evaluation which included visual inspection and Zyglo. In general, the surface quality of the inerted heats was considerably better than that of air-melted castings. This was not unexpected in view of the lower oxygen and hydrogen contents in metal and decreased slag formation and reoxidation of alloys. Table 6 lists casting reject rates for various grades of LBI heats along with the comparative data for air-melted heats.

These results show the rejection rate due to the defects which are metal and mold related: slag and ceramic inclusion, gas holes (porosity), cold shuts, shrinkage and cracks. Because of the reduction in oxygen and hydrogen contents and decreased slag carryover, reduction in rejections due to these particular defect types would be expected.

Table 6 shows reject rates due to the above-mentioned causes. On a specific part basis, LBI heats enjoyed significantly lower rejection rates than did comparable air-melted heats. In general depending on the steel grade and the part, the reject rates were 20 to 100% lower for the LBI heats. LBI heats showed a particularly marked reduction in gas hole and slag inclusion type defects.

Inerting Gas Costs

The tests have shown total gas Costs for N_2 and Ar to be in the range of \$0.07 to \$0.17 per pound of metal depending on heat times. These calculations assume a constant inerting gas flow throughout the heat and a practice which results in similar or slightly lower metal nitrogen contents compared to air-melt practice. Further process optimization based on reduced gas flow rates during the initial stages of melting offer significant potential to further reduce inerting cost. Additional savings are possible if higher nitrogen levels are desired or can be tolerated.

Inert Gas Safety

Since relatively high flow rates of inert gases were used in these tests, strict attention was paid to safety issues. The atmosphere around the furnace was monitored for oxygen deficiency. The areas around the furnace were found to have normal oxygen levels posing no danger to operating personnel. A plume of hot inert gases and oxygen deficiency exists in the region immediately above the furnace up to a height of 3 to 4 feet. This introduces a further hazard to the high temperatures and toxic metal vapors already present in this plume, and added precautions should be taken to prevent personnel exposure to this plume.

ACKNOWLEDGMENTS

A project of this magnitude required a high degree of cooperation between various departments at both Linde and the client foundry for its success. The authors would like to express their sincere thanks to the colleagues without whose help it would not have been possible to achieve these results. In particular, we would like to thank R. J. Selines, K. A. Lyttle, C. J. Messina, A. R. Barlow, P. S. Gravely and Wendy Hug-Granato of Linde Div. and shop personnel of the foundry for their help during and after the inerting trials.

REFERENCES

1. Francis, A. W. Jr. et al., Process for Reducing Backmixing, US patent 4,448,616, May 15, 1984.

2. Nowotarski, M. S., Wide Laminar Fluid Doors, US patent 4,823,680, April 25, 1989.

3. Nowotarski, M. S., Fluxless Application of a Metal-Comprising Coating, US patent 4,821,947, April 18, 1989.

Table 1: Nominal Composition of Alloys

%	17-4PH	CK-20	CF-8M	Ni-Base	Co-Base	Monel	Carbon	8620	4140
C	.07X	.20X	.08X	.20X	.20-.30	.30X	.30X	.15-.25	.35-.45
Mn	.70X	1.50X	1.50X	1.OX	.40-.60	1.50X	.70X	.60-1.00	1.00X
Si	1.00x	1.50X	1.50X	1.OX	.75-1.00	3.5-4.5	.60X	.60-.80	.80x
Cr	15.5-17.7	23.0-27.0	18-21	20.5-23.0	28.5-30.5		.50X	.40-.70	.75-1.10
Ni	3.6-4.6	12.0-15.0	9-11.0	Bal.	9.5-11.5	Bal.	.40X	.40-.70	
Mo		.50X	2-3.0	8.0-10.0			.20X	.15-.25	.15-.25
Cu	2.5-3.2					27.0-33.0	.30X		
Co				0.5-2.50	Bal.				
W					6.5-7.5				
Cb	.15-.35								
N	.05X								
Fe	Bal.	Bal.	Bal.	17.0-20.0	2.0X	2.5	Bal.	Bal.	Bal.

Table 2: Oxygen Concentration in Metal at Tap

Grade	LBI Heats,	Air-Melted,	% Reduction in Oxygen Level
CF-8M	0.0100±0.0014	0.0190±0.0033	47.4
CK-20	0.0140±0.0029	0.0200±0.0026	30.0
Ni-Base	0.017	0.019	10.5
17-4 PH	0.013	0.018	27.8
Co-Base	0.017	0.031	45.2
8620	0.0045	0.0120	62.5
4140	0.0063±0.0011	0.0075	16.0

Table 3: Nitrogen Concentration in Metal at Tap*

Grade	LBI Heats, %	Air-Melted, %
CF-8M	0.050	0.055
CK-20	0.086	0.092
Ni-Base	0.045	0.042
17-4PH	0.048	0.050
Co-Base	0.068	0.091
8620	0.013	0.013
4140	0.017	0.020
Carbon	0.011	0.012

* LBI practice designed to keep N_2 levels similar to those in air melted heats.

Table 4: Hydrogen Concentration in Metal

Grade	Sample Time	LBI Heats ppm	Air-Melted, ppm	% Reduction in H2 by Inerting
Monel	Before Ar Degassing	2.00	3.27	38.8
	After Ar Degassing	1.18	2.70	56.3
	% Hydrogen Removal	41.0	17.4	
17-4 PH	Melt Down	3.30	6.50	49.2
	Tap	1.55	6.20	75.0
	% Hydrogen Removal	53.0	4.6	
Co-Base	Melt Down	2.94	--	
	Tap	2.40	9.85	75.6
	% Hydrogen Removal	15.6		

Table 5: Oxidation of Alloying Elements

Grade	% Oxide in Slag			Percent Reduction by LBI
		Air-Melted	LBI	
CF-8M	Cr_2O_3	20	7	65.0
	MnO	13	5	61.5
CK-20	Cr_2O_3	18	6	66.7
	MnO	9	2	77.8
8620	Cr_2O_3	2.7	0.7	74.1
	MnO	27	13	51.0
	FeO	8.4	1.6	81.0
4140	Cr_2O_3	1.4	0.3	78.6
	MnO	17	3.5	79.4
	FeO	4.9	0.6	87.8

Table 6: Casting Rejection Rates for LBI and Air-Melted Heats

Grade	Casting ID	Casting Defects and Rejection Rates, %							
		LBI				Air-Melted			
		GH+SL	NF	CS+CI SK+CR	Total	GH+SL	NF	CS+CI SK+CR	Total
CF8M	1354	0	0	0	0	0.8	11.4	6.5	18.7
CF8M	1356	4.1	0.5	3.9	8.5	4.5	0.36	3.6	8.46
Co-Base	1779	0	1.0	0.33	1.33	0	1.1	.l	8.2
Ni-Base	1753	0	0	20.9	20.9	0	0	25.9	25.9
17-4PH	1940	0	0	0	0	1.34	0.14	0.96	2.44
Monel	1717	0	0	0.5	0.5	11.1	0	0	11.1
Monel	1718	5.8	0	0.8	6.6	11.8	0.6	0	12.4
CK-20	1747	0	0	0	0	0	0	10.9	10.9

GH + SL - Gasholes (porosity) and slag
NF - Non-Fill
CS+CI+SK+CR - Cold Shut, Ceramic Inclusion, Shrink and Cracks

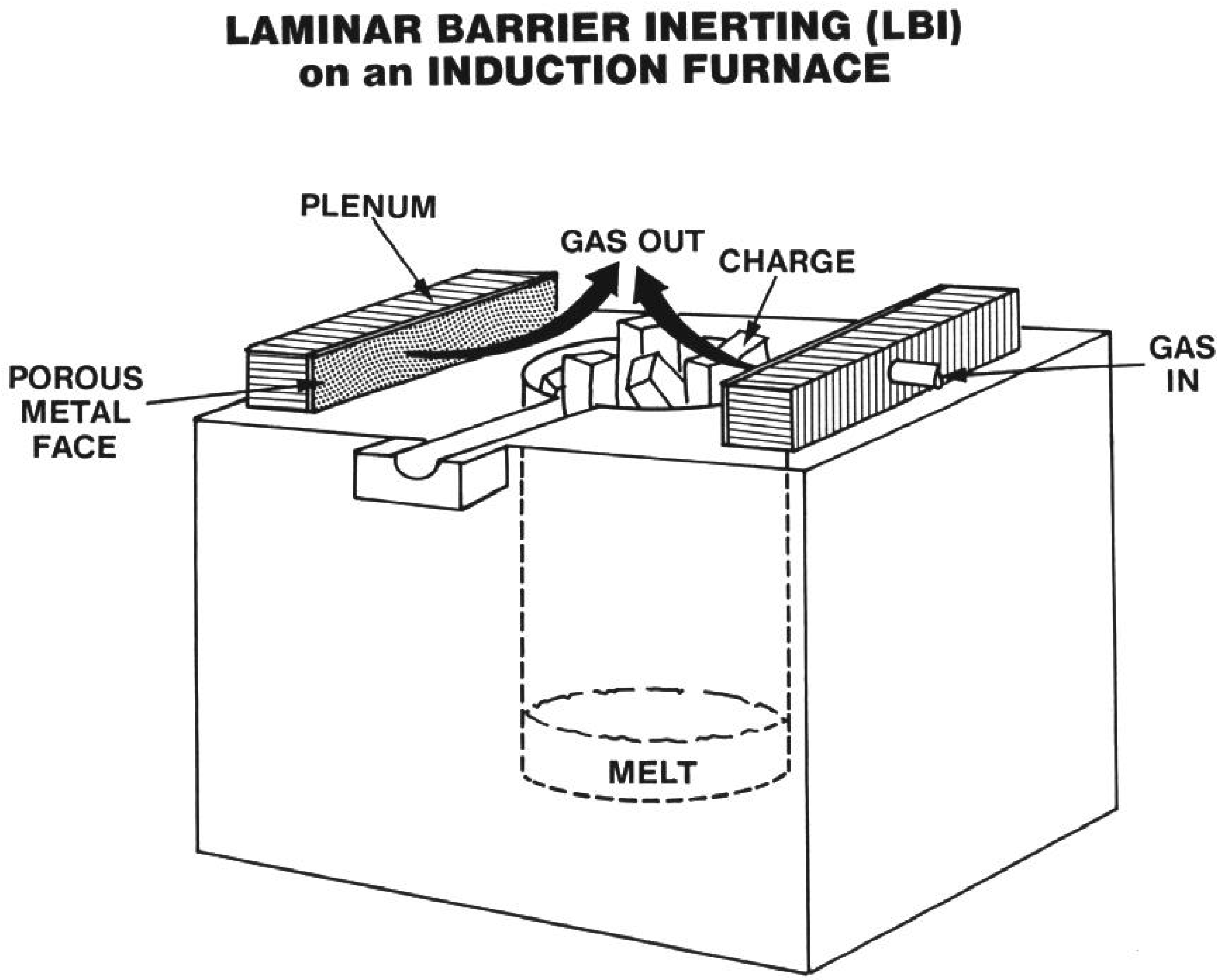

Figure 1: Schematic of Laminar Barrier Inerting on an Induction Furnace

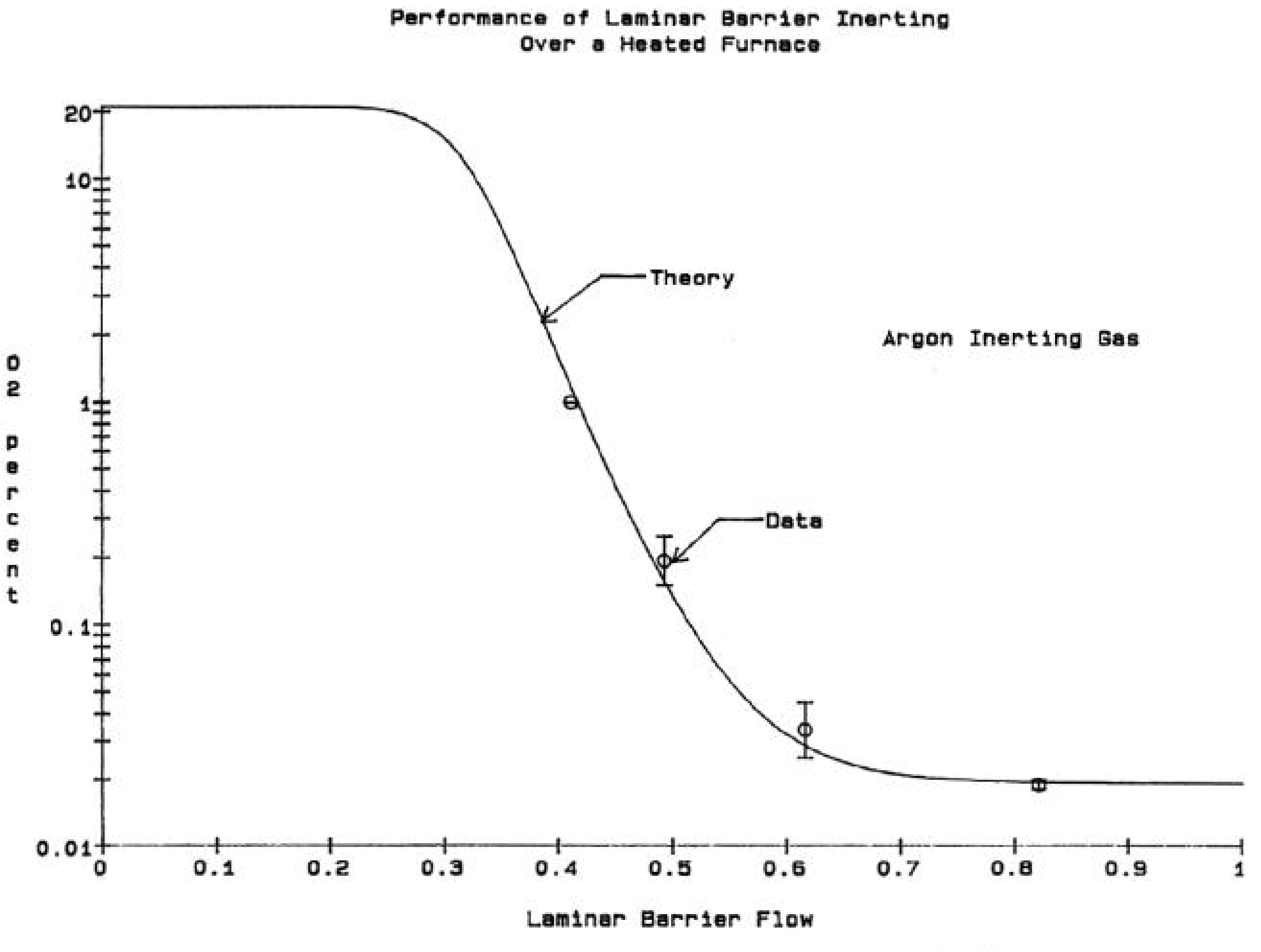

Figure 2: Headspace Oxygen Content as a Function of Laminar Barrier Flow.

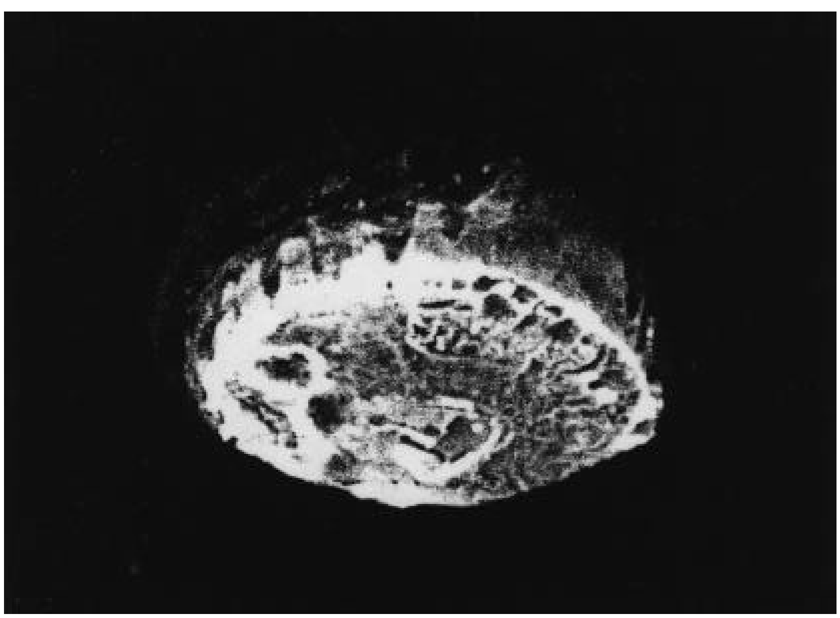

Figure 3: Slag Formation in Air-Melted Heats

Figure 4: Slag Formation in LBI Heats