

# USE OF HBI AND DRI FOR NITROGEN CONTROL IN STEEL PRODUCTS

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## SYNOPSIS

In recent years, there has been a substantial increase not only in the production of steel via the EAF route, but also the production of 'high-end' steel products by this route. The stringent quality requirements of flat products and special bar quality (SBQ) end users demands that steel nitrogen levels are kept to a consistent minimum.

HBI and DRI are a suitable raw materials for dilution of residual elements, however they are often overlooked as a reliable means of reducing dissolved gases, especially nitrogen, in the final product. As well as a dilution effect there is evidence that melting of HBI and DRI results in lower nitrogen levels at low addition levels. The in situ carbon content of HBI/DRI (present as both finely dispersed free carbon, and as iron carbide particles) is much more efficient to promote carbon boil reactions than large batch additions of lump coke and similar materials.

The manner in which nitrogen enters the steel in the EAF, and the strategies for minimising nitrogen levels are discussed. The effects of nitrogen on steel processing and product properties are also described.

Results from various EAF plants using HBI/DRI are presented and analysed, demonstrating improved nitrogen control, process efficiency and product properties. Further, it is shown that using HBI and DRI to achieve these improvements optimises productivity and cost of the EAF and downstream processes.

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## 1.0 INTRODUCTION

Over the last 40 years, the proportion of steel produced via the EAF route has been steadily increasing. EAF steel production in 2000 was 286 million tonnes, which accounted for 34% of global steel production [1]. EAF steelmakers have traditionally been producers of long products and lower quality steel products, but have become increasingly involved in production of flat products and SBQ. The IISI have quantified this trend by forecasting an increase in the production of flat products via the EAF route from 20 to 68 Mt/a by 2010. [2]

‘High-end’ steel products have stringent nitrogen specifications. For example deep drawing applications require nitrogen levels below 50 ppm [2]. Further, steel produced via the EAF route is typically higher in nitrogen than that produced via the BOF, as shown in Table 1. Therefore increasingly strict control of nitrogen is becoming necessary during the EAF steelmaking process.

*Table 1: Typical nitrogen content of steel produced via the BOF and EAF [2]*

Process	Nitrogen content of steel at tap
EAF (scrap-based)	40-110 ppm
BOF	10-40 ppm

Steelmakers use several strategies in order to control nitrogen in the EAF, including foamy slag practice, CO boil during refining, and the use of low nitrogen feed materials, such as HBI and DRI.

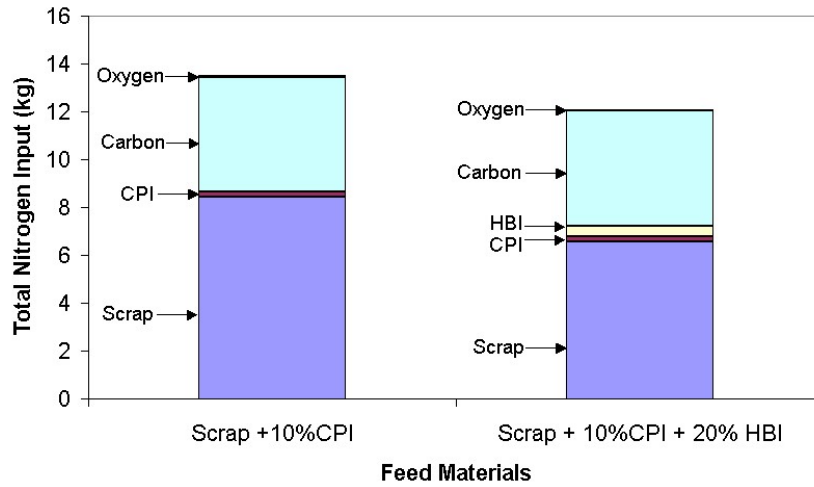
## 2.0 SOURCES OF NITROGEN IN EAF STEELMAKING

Nitrogen present in steel products has two main sources: the nitrogen that is present in the feed materials, such as scrap; and the nitrogen that is absorbed from the atmosphere during the steelmaking process. Table 2 shows the amount of nitrogen present in each of the feed materials typically used in the EAF. Molinero et al have determined the nitrogen content of a wide range of ferrous materials, carbonaceous materials, alloys and slag formers, presented elsewhere [3].

*Table 2: Nitrogen content of feed materials used in EAF steelmaking [3-8]*

Feed Material	Nitrogen Content
Scrap	30-120 ppm
HBI/DRI	20-30 ppm
Liquid iron from the BF	60 ppm
Cold pig iron (CPI)	20-30 ppm
Hot heel	10 ppm
Coke	5000-10000 ppm
Oxygen	30-200 ppm
Carbon Carrier Gas (Air)	78%
Bottom stirring gas (N <sub>2</sub> )	>99.9%
Bottom stirring gas (Ar)	<30 ppm
CaO	400 ppm

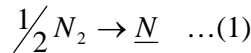
It is apparent from this data that virgin iron units such as HBI and DRI contain considerably less nitrogen than recycled iron units such as scrap. Figure 1 shows that the use of HBI dilutes the nitrogen content of the input materials.



**Fig. 1** Effect of raw materials on total nitrogen input for an 85 tonne charge, assuming coke rate of 10 kg/t and oxygen rate of 20 Nm<sup>3</sup>/t [After 3-8]

## 2.1 Mechanisms of Nitrogen Absorption

Nitrogen gas is absorbed into liquid iron from the atmosphere in two ways. The first is via diatomic dissociation, as given in Equation (1).



The equilibrium constant for nitrogen absorption is therefore:

$$K_N = \frac{a_N}{(p_{N_2})^{1/2}} \quad \dots(2)$$

If we assume that the activity of the nitrogen dissolved in the steel is approximately the same as the chemical concentration (Henry's law), then this concentration can be calculated as:

$$\% \underline{N} = K_N \cdot (p_{N_2})^{1/2} \quad \dots(3)$$

Hence, the greater the partial pressure of nitrogen in the atmosphere near the air/steel interface, the greater the absorption of nitrogen into the liquid steel. In simple terms, the more nitrogen in the atmosphere, the greater the nitrogen pickup during the steelmaking process. This has particular implications when nitrogen gas or air is used for stirring or carbon injection.

The second means of nitrogen absorption is from monatomic nitrogen. Molecular nitrogen dissociates to form monatomic nitrogen at the very high temperatures present in the plasma arc in the EAF. This in turn, is readily absorbed into the steel bath. This phenomenon is represented by Equations (4) and (5):

$$\frac{1}{2}N_2(g) = N(g) \quad \dots(4)$$

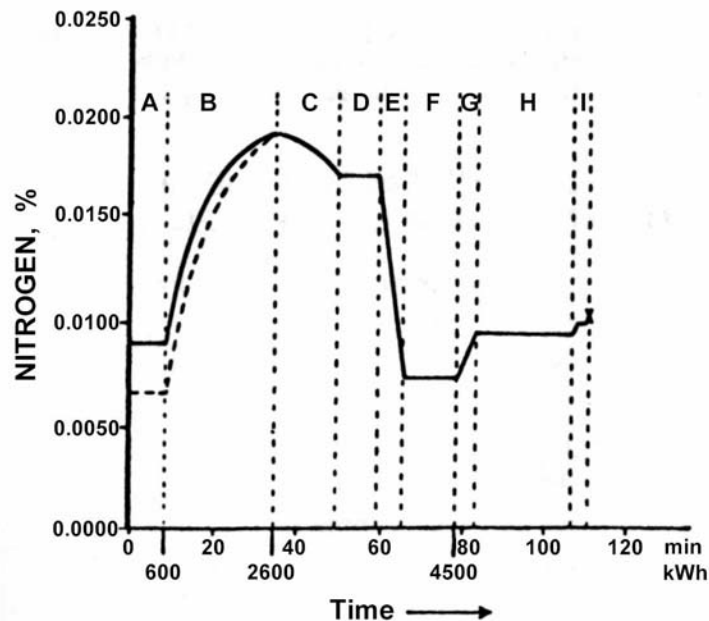
$$N(g) = \underline{N} \quad \dots(5)$$

Equations (2) and (3) still hold for this second mechanism of nitrogen absorption, since the overall reaction is the same. However, when the plasma arc is present it exerts such force on the slag, that it exposes the liquid steel. Further,  $K_N$  is a function of temperature, such that the reaction proceeds to a greater extent at higher temperatures, such as those that exist near the arc. This promotes absorption of nitrogen present in the arc, and so the arc has greater influence on nitrogen absorption than the incidental atmosphere.

## 2.2 Nitrogen Levels During the Steelmaking Process

A study conducted by Pilliod [9] has demonstrated the change in nitrogen content in the steel bath during melting and refining in the EAF, as represented in Figure 2. The solid line represents heats using 50% foundry returns and 50% scrap, while the dashed line represents heats using 100% scrap. The various stages of the steelmaking process are labelled alphabetically and represent:

- A: Electrodes boring through cold charge
- B: Small molten pool forms and increases
- C: Remaining charge melted
- D: Bath heated to carbon boil temperature
- E: Carbon boil period
- F: Ferroalloy additions made and bath heated to tapping temperature
- G: Tapping of the heat
- H: Molten steel held in tap ladle
- I: Molten steel re-ladled and cast



*Fig. 2 Nitrogen content in steel bath during EAF melting and refining [9]*

It should be noted that although Pilliod’s work is significant, stage F – the addition of ferroalloys in the EAF – is no longer typical practice for EAF steelmakers. Since Pilliod reports that this stage has no effect on nitrogen levels, the data remain valid.

The only time during the process that the nitrogen content decreases is during stages C and E. During stage C, a slag has formed which prevents nitrogen absorption, while the remaining melting iron units dilute the nitrogen content. In stage E, bubbles of CO generated in the steel adsorb dissolved nitrogen and remove it to the atmosphere. This will be discussed further in Section 4.3.

## 2.4 Nitrogen Specifications

Table 3 shows the typical nitrogen specifications and achieved nitrogen levels for various long and flat steel products. Invariably, the actual nitrogen levels are less than the required specification.

*Table 3 Nitrogen specifications and actual levels for various steel products [2]*

Product		N spec. (ppm)	Actual N (ppm)
Long Products	Special Bar Quality	70-90	30-60
	Structural	80-150	50-70
	Rod	50-150	20-60
	Merchant Bar	90-130	40-60
Flat Products	Super Extra Drawing Quality (SEDQ)	50-60	30-40
	Electro-galvanised	25-150	20-80
	Commercial Quality	60-150	30-60
	High-Strength Low Alloy (HSLA)	60-90	20-70

## 3.0 EFFECT OF NITROGEN ON STEEL PROCESSING AND PROPERTIES

### 3.1 Behaviour of Nitrogen in Steel

While steel is liquid the nitrogen present exists in solution. However, solidification of steel may result in three nitrogen-related phenomena: formation of blowholes; precipitation of one or more nitride compounds; and/or the solidification of nitrogen in interstitial solid solution.

The maximum solubility of nitrogen in liquid iron is approximately 450 ppm, and less than 10 ppm at ambient temperature, as shown in Figure 3 [10]. Further, the presence of significant quantities of other elements in liquid iron affects the solubility of nitrogen. More importantly, the presence of dissolved sulphur and oxygen limit the absorption of nitrogen

because they are surface-active elements. This is exploited during steelmaking to avoid excessive nitrogen pickup, particularly during tapping, as will be discussed in Section 4.2.

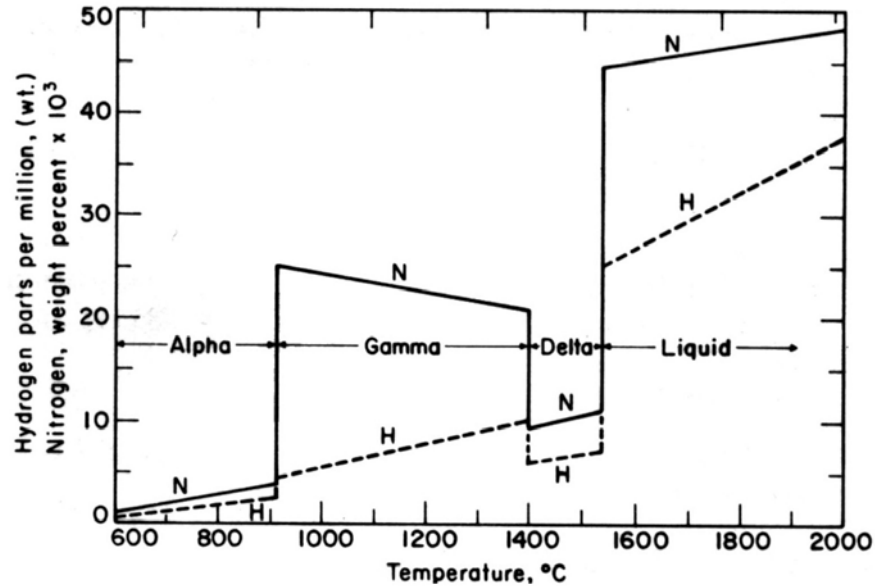


Fig. 3 Solubility of nitrogen in iron for temperatures of 600-2000°C [10]

Similar to nitrogen, there is a significant solubility differential for hydrogen in iron, with respect to temperature, as shown in Figure 3. Therefore, as steel solidifies, excess nitrogen and hydrogen are rejected from the solid material, and the concentrations of nitrogen and hydrogen in the liquid steel increase. The same is true of oxygen, however, oxygen will react with carbon to produce carbon monoxide (CO). If the total gas pressure generated by the nitrogen, hydrogen and CO satisfies Equation (6), bubbles of gas may form, resulting in blowholes in the cast structure.

$$p_{H_2} + p_{N_2} + p_{CO} > P_s + P_f + \frac{2\sigma}{r} \dots(6)$$

where  $p$  is the partial pressure of the respective gases,  $P_s$  is the atmospheric pressure on the surface of the solidifying steel,  $P_f$  is the ferrostatic pressure at the location of blowholes and  $\sigma$  is the surface tension of the liquid steel in contact with the gas bubble of radius,  $r$ . Generally, the sum of the partial pressures of the gases must be greater than 1.05 atmospheres in order to form blowholes just below the surface of the cooling steel. [11]

If there is insufficient gas pressure to form blowholes, the remaining nitrogen in excess of the maximum nitrogen solid solubility, will agglomerate as precipitates at dislocation sites. In the absence of alloying elements,  $Fe_4N$  will form, however, these precipitates induce strain ageing in deep drawn products. Therefore, other alloys such as aluminium, vanadium and niobium are added to produce alternative precipitates that can improve mechanical properties. Most commonly, nitrogen will form aluminium nitrides in low carbon aluminium-killed (LCAK) steels. [12]

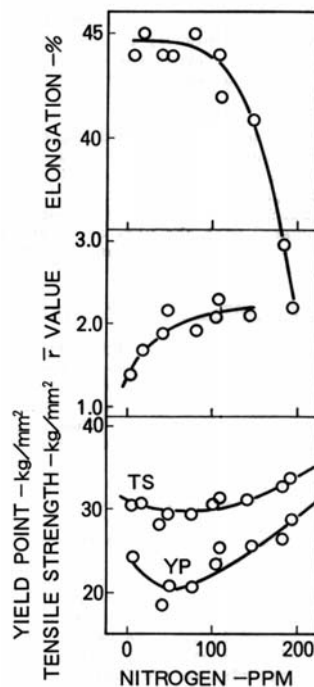
The soluble component of nitrogen is commonly referred to as ‘free nitrogen’. Like carbon, nitrogen atoms are significantly smaller than iron atoms and exist within the interstices in the atomic structure. This atomic arrangement is known as an interstitial solid solution. [12]

### 3.2 Effect of Nitrogen on Steel Properties

The effect of nitrogen on steel properties can be either detrimental or beneficial, depending on the other alloying elements present, the form and quantity of nitrogen present, and the required behaviour of the particular steel product. In general, however, most steel products require that nitrogen be kept to a minimum. High nitrogen content may result in inconsistent mechanical properties in hot-rolled products, embrittlement of the heat affected zone (HAZ) of welded steels, and poor cold formability. In particular, nitrogen can result in strain ageing and reduced ductility of cold-rolled and annealed LCAK steels. [13]

#### 3.2.1 Effect of Nitrogen on Formability

Figure 4 shows that the strength of LCAK steels decreases slightly and then increases with increasing nitrogen. Conversely, the elongation decreases and the r-value increases with increasing nitrogen. The r-value is the average ratio of the width to thickness strain of strip tensile specimens tested in various orientations [14]. It is an inverse measure of formability. Hence, high nitrogen content leads to poor formability of LCAK steels, even after annealing.

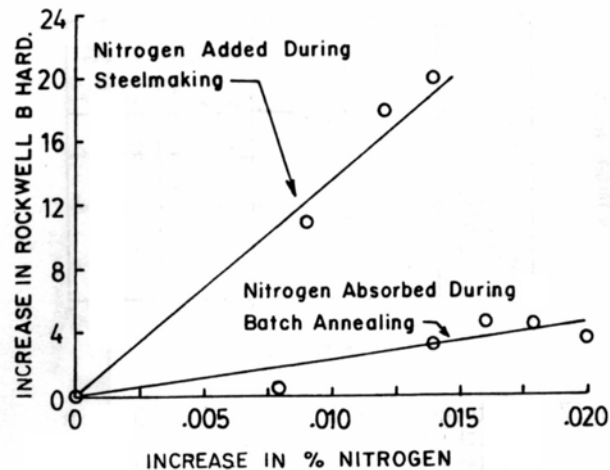


*Fig. 4 Effect of nitrogen on yield strength, tensile strength, r-value and elongation of LCAK steel in the annealed condition [15]*

The effect of nitrogen on mechanical properties is the result of interstitial solid solution strengthening by the free nitrogen; precipitation strengthening by aluminium and other nitrides; and grain refinement due to the presence of nitride precipitates. [16]

### 3.2.2 Effect of Nitrogen on Hardness

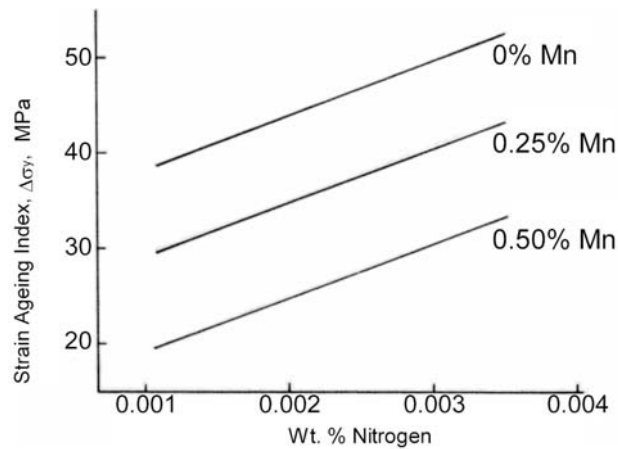
Hardness is the resistance of a material to surface indentation. Figure 5 shows that hardness increases linearly with increasing nitrogen content. Nitrogen absorbed during steelmaking results in interstitial solid solution strengthening and grain refinement, both of which increase hardness. Further, the diagram shows that nitrogen absorbed during the steelmaking process has a more significant impact than that absorbed during batch annealing in a nitrogen-rich atmosphere, although both have a measurable effect. [12, 17]



*Fig. 5 Increase in hardness of aluminium-killed sheet steel with respect to increasing nitrogen content [17]*

### 3.2.3 Effect of Nitrogen on Strain Ageing

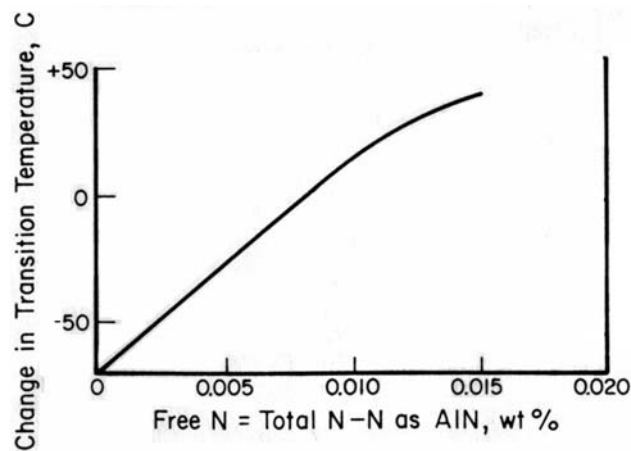
Strain ageing occurs in steels containing interstitial atoms, predominantly nitrogen, after they have been plastically deformed. After deformation, the nitrogen segregates to dislocations causing discontinuous yielding when further deformed. Not only does strain ageing result in increased hardness and strength, and reduced ductility and toughness, but it may also result in the appearance of 'fluting' or 'stretcher strains' on the surface of deformed material. [18, 19] Duckworth and Baird [14] have developed a measure of strain ageing termed 'strain ageing index'. This is based on an empirical equation to calculate the increase in yield stress when deformed material is held for 10 days at room temperature. Figure 6 shows that increasing nitrogen results in a higher strain-ageing index, and therefore greater propensity for surface defects.



**Fig. 6** Effect of nitrogen on strain ageing in mild steels with varying manganese content [19 after 14]

### 3.2.4 Effect of Nitrogen on Impact Properties Including Welded Material

The ability of a material to withstand impact loading is commonly known as toughness. It is sometimes quantified by measuring the amount of energy that is absorbed by a test piece of known dimensions prior to fracture. It is further analysed by determining the fracture mechanism upon impact over a range of temperatures. As temperature is decreased, the fracture type will change from fibrous/ductile to crystalline/brittle. This arbitrary temperature is termed the 'ductile-to-brittle' transition temperature. The lower the transition temperature the better the impact properties, since failure via ductile fracture may be less catastrophic than that via brittle failure. [20] Figure 7 demonstrates that as free nitrogen increases, the transition temperature increases, and therefore toughness decreases. This is attributed to solid solution strengthening. [21]



**Fig. 7** Effect of free nitrogen on impact properties [22]

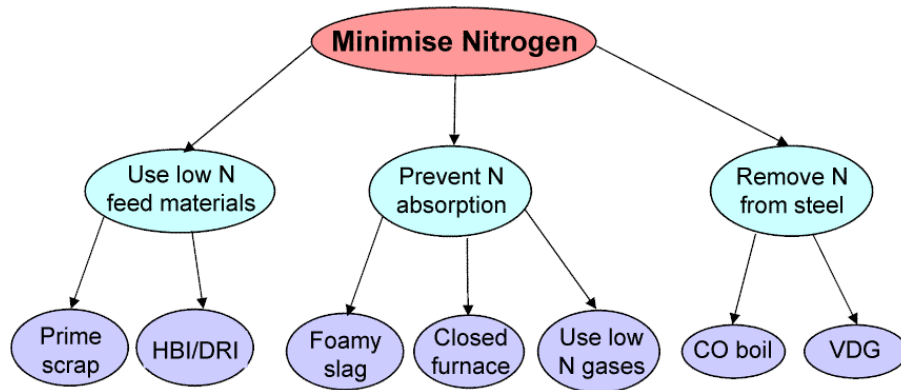
Conversely, limited amounts of nitrogen present as precipitates have a beneficial effect on impact properties. Nitrides of aluminium, vanadium, niobium and titanium result in the formation of fine-grained ferrite [16]. Further, the smaller the grain size the lower the

transition temperature, hence improved toughness [23]. Therefore, it is necessary to carefully control, not only the nitrogen content, but also the form in which it exists, in order to optimise impact properties.

Nitrogen is known to affect the toughness of the heat-affected zone (HAZ) of welded steel. This is important, since the weld metal should not be a point of weakness in a welded structure. This loss in toughness is often referred to as HAZ embrittlement. It is thought this occurs when the nitrides present in the HAZ are dissociated as a result of the elevated temperatures that exist during welding. The absence of precipitates results in grains of larger diameter. Also, the metal cools quickly producing low toughness martensite or bainite, which contain high levels of free nitrogen further exacerbating the loss of toughness. Using lower heat input and several passes to prevent dissociation of the nitrides may prevent this. [19]

#### 4.0 NITROGEN CONTROL DURING STEELMAKING

There are several ways in which nitrogen can be controlled during the EAF steelmaking process. This section will evaluate the merits of the various options: use of low nitrogen feed materials; prevention of nitrogen absorption; and, removal of nitrogen from the steel prior to casting. Figure 8 is a pictorial representation of the main options available for minimisation of nitrogen.



*Fig. 8 Strategies for minimising nitrogen during the EAF steelmaking process*

#### 4.1 Use of Low Nitrogen Feed Materials

Use of low nitrogen raw materials will provide dilution of the nitrogen in the steel bath. These materials may include hot metal, prime scrap, pig iron and/or HBI/DRI. However, there are limitations to the use of each material.

Hot metal not only provides virgin iron units, but also contributes heat energy to the process. However, hot metal is only available at those plants with blast furnace or Corex® facilities and has higher nitrogen levels than HBI/DRI and cold pig iron. Prime or prompt industrial scrap is low in nitrogen and residual elements, however it commands a price premium and is not readily available in some geographical regions. Cold pig iron is a virgin iron unit, which

also provides substantial carbon and hence chemical energy, but may contain significant quantities of sulphur and phosphorus. HBI and DRI also contain very low nitrogen contents and no residual elements. The gangue present in HBI/DRI can be used to advantage as discussed in Section 4.2.

A plant-based study by Thomas et al has shown that, when using recycled iron units only, there is little relationship between the total nitrogen added in the charge and the meltdown nitrogen. Thomas proposes that an alternative phenomenon is a more dominant influence on steel nitrogen levels. [7] Pilliod's work supports this assertion (see Figure 2, Region B), and specifies that significant nitrogen absorption occurs during initial melting when there is insufficient slag present to shield the liquid steel. [9] This will be discussed further in Section 4.2.

## 4.2 Prevention of Nitrogen Absorption from the Atmosphere

Figure 2 shows that the liquid steel absorbs significant quantities of nitrogen from the atmosphere during the early stages of melting. Formation of a slag as early as possible will provide a barrier between the steel and the atmosphere. Boodarie<sup>TM</sup> Iron contains about 3% gangue, comprised of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, K<sub>2</sub>O, TiO<sub>2</sub>, MgO, and P<sub>2</sub>O<sub>5</sub>, as well as about 7% FeO. These oxides provide the basis of a slag that promotes shielding from the atmosphere. Fruehan et al have asserted this mechanism of shielding based on laboratory studies of nitrogen control using MIDREX<sup>®</sup> DRI [24, 25].

Carbon monoxide from the liquid steel generates a foamy slag. Sometimes, carbon and oxygen are deliberately injected into the slag to make it foamy. In the case of high carbon HBI/DRI, the slag may foam in the early part of the process [26]. This not only shields the steel from the atmosphere, but also covers the arc, which minimises the dissociation of nitrogen molecules and therefore prevents nitrogen absorption.

It is thought that utilisation of a 'closed furnace' practice will minimise nitrogen absorption from the atmosphere. Such a practice requires that the furnace is well sealed and that the doors and roof are not opened unnecessarily. Continuous feeding of the charge material is amenable to this practice, particularly fifth hole charging of DRI or HBI. A comprehensive study by the IISI revealed that 'closed furnace' practice has not been adopted as a standard practice for nitrogen control. [2]

Other simple practices can assist in nitrogen minimisation. These include the use of nitrogen-free stirring gases and carrier gases. Argon gas used to stir the steel in the ladle can remove nitrogen to the atmosphere, and the use of argon gas, rather than air or nitrogen, for carbon and lime injection will be beneficial. However, argon is very expensive and often only available in limited quantities, so substitution of argon for air and nitrogen in these applications is impractical.

Thomas et al have reported that during tapping absorption of only 1 ppm of nitrogen is attributable to the addition of alloys. The notable exceptions are calcium silicide and coke. Of more concern is the absorption of nitrogen into the tapping stream. [7] Several strategies can assist: use of eccentric bottom tapping to ensure the tapping stream remains compact; tapping before deoxidation in order to leverage the surface active nature of oxygen; and

desulphurisation of the steel only at the ladle furnace, again to leverage the surface active nature of sulphur.

### 4.3 Removal of Nitrogen from Liquid Steel

#### 4.3.1 CO Boil

Standard practice at most EAF steelmaking shops is the CO boil. This involves a vigorous reaction between carbon and oxygen deep in the bath. The resulting bubbles of CO adsorb nitrogen as they ascend to the surface releasing both gases to the atmosphere. The CO boil is brought about by either injecting both oxygen and carbon into the steel bath, or by lancing a high carbon liquid steel with oxygen. Alternatively, oxygen may be introduced via bottom tuyeres in the furnace. [7] Region E on Figure 1 shows that this practice is highly effective in removing nitrogen from liquid steel.

#### 4.3.2 Carbon Efficiency

Thomas et al [7] have reported that the presence of DRI in the feed material can also bring about a CO boil and therefore assist in nitrogen flushing. Since DRI contains both carbon and oxygen (as an oxide of iron), it is possible to remove nitrogen even during melting. Results from North Star Steel show this to be the case as presented in Table 4.

*Table 4 Meltdown nitrogen for different proportions of charged DRI at North Star Steel [7]*

Charge	Meltdown Nitrogen (ppm)
No DRI	95
5% DRI	84
10% DRI	69

The carbon contained in HBI/DRI is present as both free carbon, and iron carbide, finely dispersed through the structure. The efficiency and consistency of carbon added is quite high, providing predictable controlled carbon boil reactions to aid in degassing and stirring. By contrast, carbon added in large batches, such as bags of coke or coal is inefficient and unpredictable. Heat to heat variation in carbon recovery is very large, with efficiency typically less than 40%. Large fireballs and sudden violent reactions are commonly associated with batch additions of coke or coal carbon sources, adding to the uncertainty of using this method for nitrogen control.

#### 4.3.3 Nitrogen Removal Mechanism

Fruehan et al have presented contrary evidence based on their studies of nitrogen removal using DRI. According to their experimental work, DRI only reduces nitrogen by dilution and generation of slag early in the melting process. They hypothesise that the CO generated by the DRI causes the pellets to become buoyant and rise to the slag phase, in which nitrogen flushing cannot be accomplished. They assert that the reaction of carbon and injected oxygen deep in the bath is more effective in removing nitrogen. [25] It has been observed during experimental work conducted by Honeyands that BHP Boodarie™ Iron has a significantly

higher density than DRI pellets. It was further observed that HBI does not float in the slag, but rather sits at the slag/metal interface, and generates a significant volume of CO gas. [8]

If the steel produced via the EAF contains excess nitrogen the final option available to the steelmaker is vacuum degassing. Liquid steel is subjected to an atmospheric pressure of close to zero – approximately 25 mbar or less - at which there is a thermodynamic tendency for nitrogen (and hydrogen) to form diatomic molecules. These are adsorbed by the argon bubbles used to stir the steel and are transported to the surface and released to the atmosphere. The effectiveness of nitrogen removal by vacuum degassing will depend on the level of sulphur in the steel since this is a surface-active element. [27] Bannenberg et al have calculated that approximately 50% of the nitrogen can be removed in approximately 15 minutes for initial nitrogen levels greater than 50 ppm. This assumes conditions of 2 ppm dissolved oxygen, 10 ppm sulphur and 1 mbar pressure. [28] Benchmarking has shown that vacuum degassing adds approximately 2% to the overall cost of steel production. Also, significant capital is required for installation of vacuum degassing equipment.

## 5.0 EFFECT OF HBI/DRI ON NITROGEN LEVELS IN EAF STEELMAKING

### 5.1 Shanghai No. 5 HBI Trial Results

Baosteel Group, Shanghai No. 5 Steel Co. Ltd. conducted a comprehensive trial program using BHP's Boodarie™ Iron HBI. A description of the trial regime has been presented previously by Trotter et al [29].

The results of the trials showed that nitrogen content decreased with increasing use of Boodarie™ Iron (see Figure 9), as did the sulphur content of the steel product. [26] This is significant since liquid steel is more prone to nitrogen absorption at lower sulphur levels, since sulphur is a surface-active element.

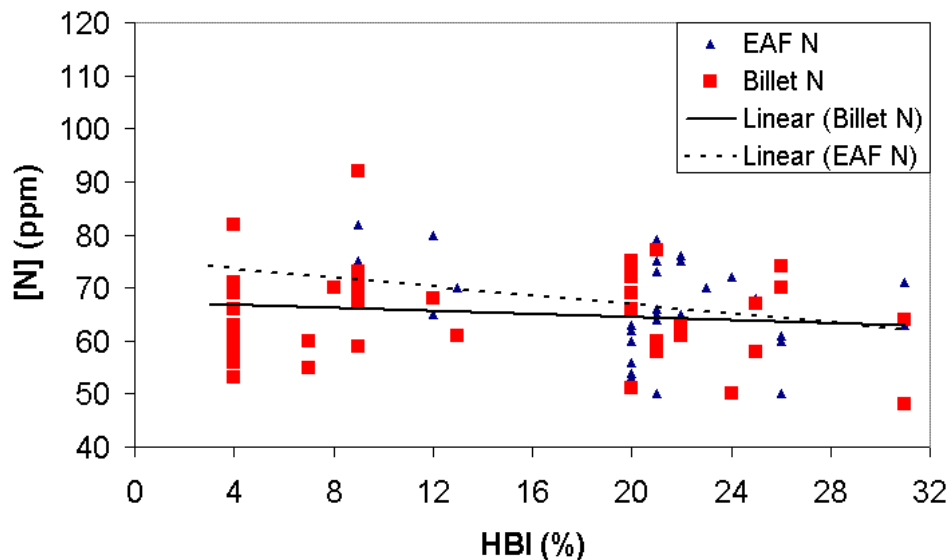


Fig. 9 Influence of HBI on Nitrogen Content in Liquid Steel [30]

Shanghai No. 5 has quantified the improvement in mechanical properties of their 40Cr and 65Mn products as a result of using Boodarie™ Iron. These are presented in Tables 5 and 6.

*Table 5 Comparison of mechanical properties of 40Cr med. C steel with 0% and 20% HBI in the feed material [30]*

	Property	Impact Toughness, Ak (J)	Elongation (%)	Reduction in Area (%)	UTS (MPa)	Yield Strength (MPa)
<b>No HBI</b>	<b>Avg.</b>	77.3	14.1	53.2	1120	976
	<b>Min-Max</b>	48-102	12-17	47-59	1040-1250	885-1110
<b>20% HBI</b>	<b>Avg.</b>	81.2	15.4	54.6	1106	949
	<b>Min-Max</b>	73-88	13-17	50-58	1080-1130	930-980

The data in Table 5 shows that using HBI provides an improvement in toughness, elongation, reduction in area, and strength. As discussed in section 3.2, these improvements result in improved formability of the steel product.

*Table 6 Rolling performance of high C 65Mn grade with 0% and 20-30% HBI in the feed material [30]*

	Cold rolled strip thickness (mm)	Reduction ratio (%)	Observation	Elongation after annealing (%)	UTS after annealing (MPa)
<b>0% HBI</b>	1.60	36	severe cracking	20-30	520-620
<b>20-30% HBI</b>	1.60	36	no cracking	25-30	520-560

The data in Table 6 quantifies the downstream benefit of using HBI. In this case, use of HBI eliminated cracking of the product during rolling. This has flow-on effects such as improved rolling mill productivity. A detailed analysis of these results was previously presented by Trotter et al [29].

Notably, Tables 5 and 6 show that the use of HBI resulted in significantly less variability in mechanical properties. This also provides downstream benefits since the customer will receive steel products with more consistent mechanical behaviour.

Further, Shanghai No. 5 has reported that the requirement to produce steels with low residual and nitrogen content demands the use of some virgin iron units. For example, there is a requirement to produce tire cord steels with less than 45 ppm nitrogen and less than 0.10% (Cu+Cr+Ni). Since they do not have an available supply of liquid iron and there is a shortage of prime scrap, merchant HBI or DRI provides a suitable alternative. [30]

## 5.2 Ispat Sidbec Inc. (ISI)

ISI have used MIDREX® DRI in quantities of 20-100% in their EAF feed material since 1973. They have observed benefits in better nitrogen control when producing a range of products including hot and cold rolled strip, rod, SBQ and wire. Since they have an in-house supply of DRI they are able to supply 75% of their required iron units and therefore have flexibility in choice of feed material. [26]

Giguere et al have reported that the iron oxide and carbon present in DRI react to produce a CO boil throughout the melting process. This flushes nitrogen from the liquid steel and also assists in the generation of a foamy slag for shielding of the steel from the arc and the atmosphere. Typically 75% DRI is used and results in meltdown nitrogen levels of 20-35 ppm. [26]

ISI have found that it is very important to achieve a preferred ratio of aluminium and nitrogen, as this determines the formation of aluminium nitrides. This results in optimum drawability of LCAK steels and prevents strain ageing. The effect of DRI on the yield-to-ultimate ratio of rimmed and aluminium-killed steels is presented in Table 7. The lower this measure, the better the formability. [26]

*Table 7 Yield to Ultimate Ratio of 1% Temper Rolled 1006 Rimmed or AK Steel for 100% Scrap or 100% DRI Practice [26]*

	<b>Rimmed 100% Scrap</b>	<b>Rimmed 100% DRI</b>	<b>Al killed practice</b>
After rolling	0.686	0.628	0.587
Aged 1 month	0.788	0.668	0.613

The experience of ISI has also shown that low nitrogen and other residual levels are essential for wire drawing of silicon-killed steels. Table 8 summarises the improvement in reduction of area (ROA) for ISI's 1008 SiK wire grade. ROA is a measure of ductility. [26]

*Table 8 Effect of feed material on ductility of wire drawing of 1008 SiK steel [26]*

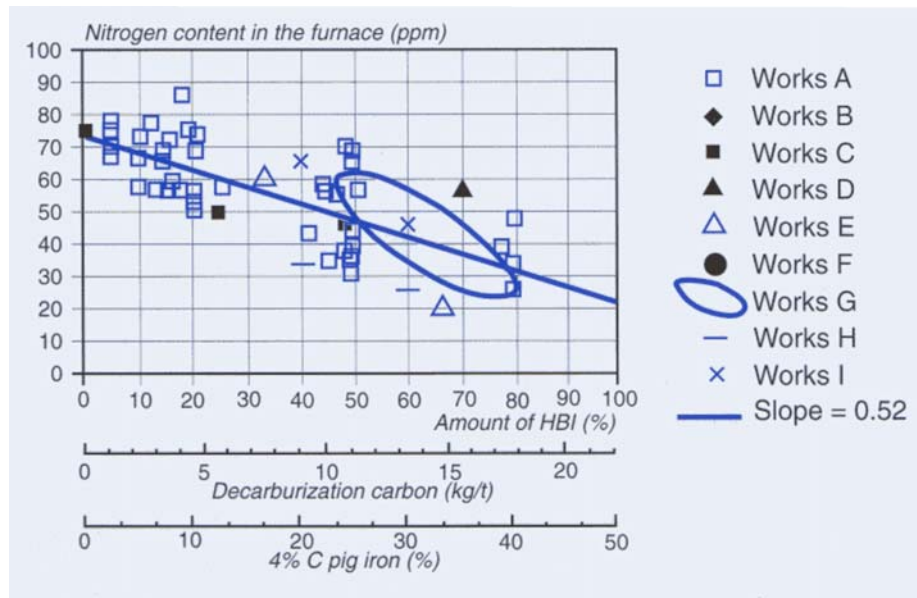
<b>Feed</b>	<b>Cu (wt %)</b>	<b>Nitrogen (ppm)</b>	<b>ROA (%)</b>
100% Scrap	0.20	80	83
100% DRI	0.05	22	95

## 5.3 Other Results

Several other steel producers have quantified the reduction in nitrogen levels in steel produced from DRI or HBI iron units. These include Nueva Montana, North Star Steel, Georgetown Steel Corporation, and several plants in the EEC. Although they have not related lower nitrogen to improvements in mechanical properties, they serve to demonstrate that nitrogen control can be achieved universally by appropriate use of DRI/HBI. The reported numbers are summarised in Table 10 and Figure 10.

**Table 10** Nitrogen content of steel at different EAF plants using different quantities of HBI/DRI [7, 31, 32]

<b>Nueva Montana Quijano Siderurgica SL, Spain</b>	%HBI	0	18.1	45.9
	Meltdown Nitrogen (ppm)	91	80	63
<b>North Star Steel – Michigan, USA</b>	%DRI	0	5	10
	Meltdown Nitrogen (ppm)	95	84	69
<b>Georgetown Steel Corp., South Carolina, USA</b>	%DRI	0	50	75
	Meltdown Nitrogen (ppm)	70	40	20



**Fig 10** Effect of HBI on meltdown nitrogen for 9 European EAF plants [2]

## 6.0 CONCLUSIONS

Due to the increasing production of flat products and other high-end steel products via the EAF steelmaking route, the requirement for strict nitrogen control is becoming ever greater. A variety of options are available to control nitrogen including improved operating practices and use of virgin iron units.

It has been demonstrated that use of HBI or DRI assists in nitrogen control by: diluting the nitrogen content of the source iron units; generating a slag early in the melting stage in order to shield the metal from the atmosphere; helping generate a foamy slag; and producing a CO boil within the steel bath to flush out nitrogen.

It has also been demonstrated that by reducing the nitrogen content of steel products, HBI can promote improvement in the mechanical properties of those products. In particular, increased use of HBI leads to improved strength, toughness, and ductility, leading to better formability. There is also evidence that use of HBI reduces susceptibility to cracking during rolling.

Further, the measurements of many steel producers show that use of HBI/DRI consistently results in lower nitrogen content than when 100% scrap is used. Combined with the added benefit of reduced residual content, use of HBI/DRI ensures greater consistency in chemical composition, and therefore steel properties. Hence, the steel producer can be confident of meeting product requirements, and minimising downgraded product and unnecessary inventory.

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