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Torn-corner defect in billets rolled from continuously cast blooms

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SYNOPSIS

This paper summarizes the investigations carried out into a defect involving the corners of billets rolled from continuously cast blooms, which broke open during the rolling process. As it was believed that the defect must be connected with the formation of subcutaneous blowholes in the bloom, the investigations were directed towards an understanding of the roles of the three gases involved in the process.

In an extensive trial programme, samples were taken from the heat at all stages of processing, as well as from all the raw materials and alloys.

The main sources of nitrogen were found to be reblows, pick-up from the alloys added to the ladle (especially graphite), and open-stream casting. The major source of hydrogen was moisture in the alloys, especially high-carbon ferromanganese and silicomanganese. Further, it was established that the moisture content of the alloys is closely related to the appearance of the defect in steels with a carbon content of less than 0,20 per cent; 72 per cent of all the defects were present in this type of steel. Most of the remaining defects were found in steels with a carbon content of more than 0,60 per cent, where the nitrogen content was substantially higher than in the lower-carbon steels.

It is suggested that the defect arises from the combined effect of oxygen, nitrogen, and hydrogen. Its occurrence in low- and high-carbon steels is triggered by the formation of subcutaneous blowholes when the critical oxygen level for carbon monoxide blowholes is lowered by the presence of excessive amounts of hydrogen and nitrogen respectively.

SAMEVATTING

Hierdie referaat gee 'n opsomming van die ondersoeke wat ingestel is na 'n defek waar die hoeke van knuppels wat van stringgietvoorblokke gewals is, tydens die walsproses oopgebreek het. Aangesien daar gereken is dat die defek met die vorming van onderskilgasholtes in die voorblok verband hou, was die ondersoeke toegespits op 'n begrip van die rol van die drie gasse wat by die proses betrokke is.

Daar is in 'n omvattende proefprogram in alle stadiums van die verwerking monsters van die smelt geneem, asook van die grondstowwe en legerings.

Daar is gevind dat die hoofbronne van stikstof herblasing, opname uit die legerings wat by die gietpot gevoeg word (veral grafiet) en oopstroomgieting is. Die belangrikste bron van waterstof is vog in die legerings, veral hoëkoolstof-ferromangaan en silikomangaan. Daar is verder vasgestel dat die voginhoud van die legerings verbonde is aan die voorkoms van die defek in staal met 'n koolstofinhoud van minder as 0,20 persent; 72 persent van al die defekte het in hierdie soort staal voorgekom. Die meeste van die oorblywende defekte het voorgekom in staal met 'n koolstof-inhoud van meer as 0,60 persent waar die stikstofinhoud aansienlik hoër as in die staalsoorte met 'n laer koolstof-inhoud was.

Daar word aan die hand gedoen dat die defek voortspruit uit die gekombineerde uitwerking van suurstof, stikstof en waterstof. Die voorkoms daarvan in lae- en hoëkoolstofstaal word gesneller deur die vorming van onderskilgas-holtes wanneer die kritieke suurstofpeil vir koolstofmonoksiedholtes onderskeidelik deur die aanwesigheid van oor-matige hoeveelhede waterstof en stikstof verlaag word.

Introduction

The Newcastle Works of Iscor Ltd is situated in northern Natal in the Republic of South Africa. The plant was commissioned in 1974, and the ten-millionth ton was tapped from the basic oxygen furnaces in June 1982. The steel production of the Works consists of continuously cast slabs and blooms. The blooms have a standard size of 315 by 205 mm, and are used for medium-section, bar, and rod-mill products, as well as billets for re-rolling.

From the start-up of the plant, an occasional but consistent defect was experienced in billets rolled to 115 mm. In the billets affected, the corners broke open during rolling, and hence the name for the defect—the torn-corner defect. Around 10 kt annually were so badly affected that the billets either had to be scrapped or an extensive rectification operation had to be carried out.

This paper summarizes the investigations carried out into the problem from the initial considerations until the cause of the defect was established.

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Initial Considerations

One of the main products of the works is a group of low-carbon, low-manganese steels for the production of wire rod. Since the three bloom casters all have metering tundish nozzles, full killing by aluminium is impossible because the nozzles become blocked with alumina. Initially, silicon was used for deoxidation, the aim being a silicon level of 0,28 per cent, with carbon and manganese contents of 0,10 per cent maximum and 0,40 to 0,60 per cent respectively.

It soon became apparent that this practice produced a very 'dirty' steel, with casting-machine breakouts and high mill rejections resulting from non-metallic inclusions of steelplant origin on the surface of the rod. These inclusions were identified as silica, which formed as a deoxidation product. According to Turkdogan[1], there is a critical ratio $[\%Si] / [\%Mn]^2$ above which only solid silica forms as the deoxidation product.

Fig. 1 gives the critical silicon and manganese contents of iron in equilibrium with silica-saturated manganese silicate at various temperatures. To avoid the formation of silica (area A), the manganese: silicon ratio would have to be adjusted so that liquid manganese silicates would form as the primary deoxidation product. So that this could be achieved at Newcastle, it was decided that the

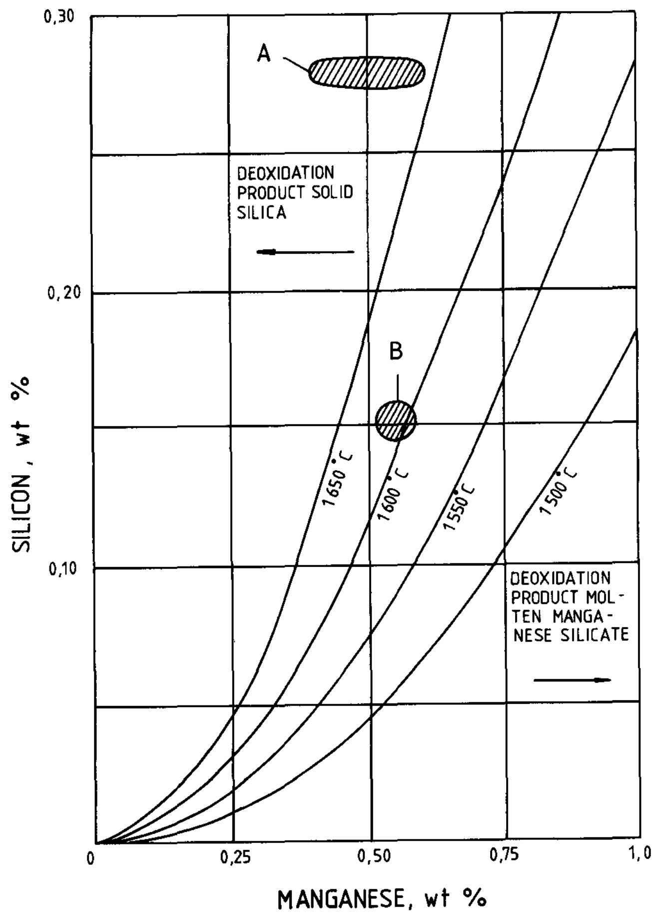

Fig. 1—Critical silicon and manganese contents of iron in equilibrium with the silica-saturated deoxidation product, which is almost pure manganese silicate (after Turkdogan[1]).

silicon level of the low-manganese steels should be reduced to an aim level of 0,15 per cent and the manganese level raised to an aim level of 0,55 per cent (area B).

No further problems with silica were encountered, but there was an upsurge in torn-corner rejections. Eventually, a deoxidation practice with a primary aluminium addition was established with an aim level of 0,15 per cent silicon and less than 0,005 per cent aluminium.

After some time, it was noticed that there were intervals when high rejections due to torn corners could be expected, and these were then followed by low rejections (Fig. 2). It was also apparent that the periods of high rejections occurred in summer, when most of the rain falls in the region.

When a breakdown of the billet qualities as a percentage of rejections was made, it was seen that the majority of the rejections were among the low-carbon, low-manganese, low-silicon qualities, with fewer rejections in the high-carbon grades.

A typical feature of the corner defect is that the defect is not readily apparent in the as-cast bloom. The defect shows only during rolling to billet. Fig. 3 represents the typical appearance of the defect in rolled billets laid out for inspection. A close-up of a defect is shown in Fig. 4.

From the very beginning, it was thought that a defect of this nature must be connected with the formation of subcutaneous blowholes in the bloom during casting. It was further believed that the source of the blowholes must be the oxygen, nitrogen, and hydrogen present, because the total pressure to form a blowhole, P_{tot}, is as follows:

$$P_{tot} = P_{CO} + P_{H_2} + P_{N_2},$$

When the sum of the partial pressures exceeds that needed for the critical radius for the formation of a gas bubble, blowholes can be formed.

To illustrate the total effect of these three gases on the formation of blowholes in continuously cast steel, a graph given by Oeters *et al.*[2] was redrawn to correspond to the extremely rapid solidification conditions at the mould wall. This graph (Fig. 5) confirms the initial assumption that the gases are interrelated, and any combination of the three will indicate whether the critical total concentration is exceeded and whether blowholes will form.

At that stage, it was decided that all the efforts should be directed towards an understanding of the roles of nitrogen and hydrogen.

Experiments Conducted

An extensive trial programme was planned on the establishment of the exact stages at which the nitrogen and hydrogen enter the system. The nitrogen levels were determined from samples taken at all the processing stages: at the end-point, after possible reblows, from the transfer ladle after tapping and after rinsing, and from the mould during continuous casting.

The potential sources of the hydrogen were considered to be as follows: moisture in the raw materials or rust on the scrap charged into the furnaces, moisture in the alloys added into the transfer ladle, moisture from the refractories, decomposition of the hydrocarbons in the casting lubricating oil and refractories, and the humidity of the atmosphere. Of these, the measurable ones were moisture in the raw materials (lime, dolomite, fluorspar, sinter) and alloys (ferrosilicon, silicomanganese, high-carbon ferromanganese, low-carbon ferromanganese, carbon, and aluminium), and the rainfall on the site as a reflection of the humidity.

As a result, all the raw materials and alloys were sampled once a week, and the moisture content was established by heating of the samples to 110°C for 1,5 hours, after which the difference in mass was recorded. The rainfall was monitored daily. Simultaneously, the daily rejections of billets with torn corners were recorded for each quality, based on the dates on which the defective casts were actually made.

Results

Nitrogen

The main sources of nitrogen were established as reblows, pick-up from the alloys added to the ladle, and the open-stream in casting from ladle to tundish and from tundish to mould. Table I summarizes the effect of the reblows and open-stream casting.

For heats that were tapped at less than 0,10 per cent carbon and that had no graphite added for recarburization, there was little difference in the nitrogen contents of the vessel and the ladle samples, indicating that no

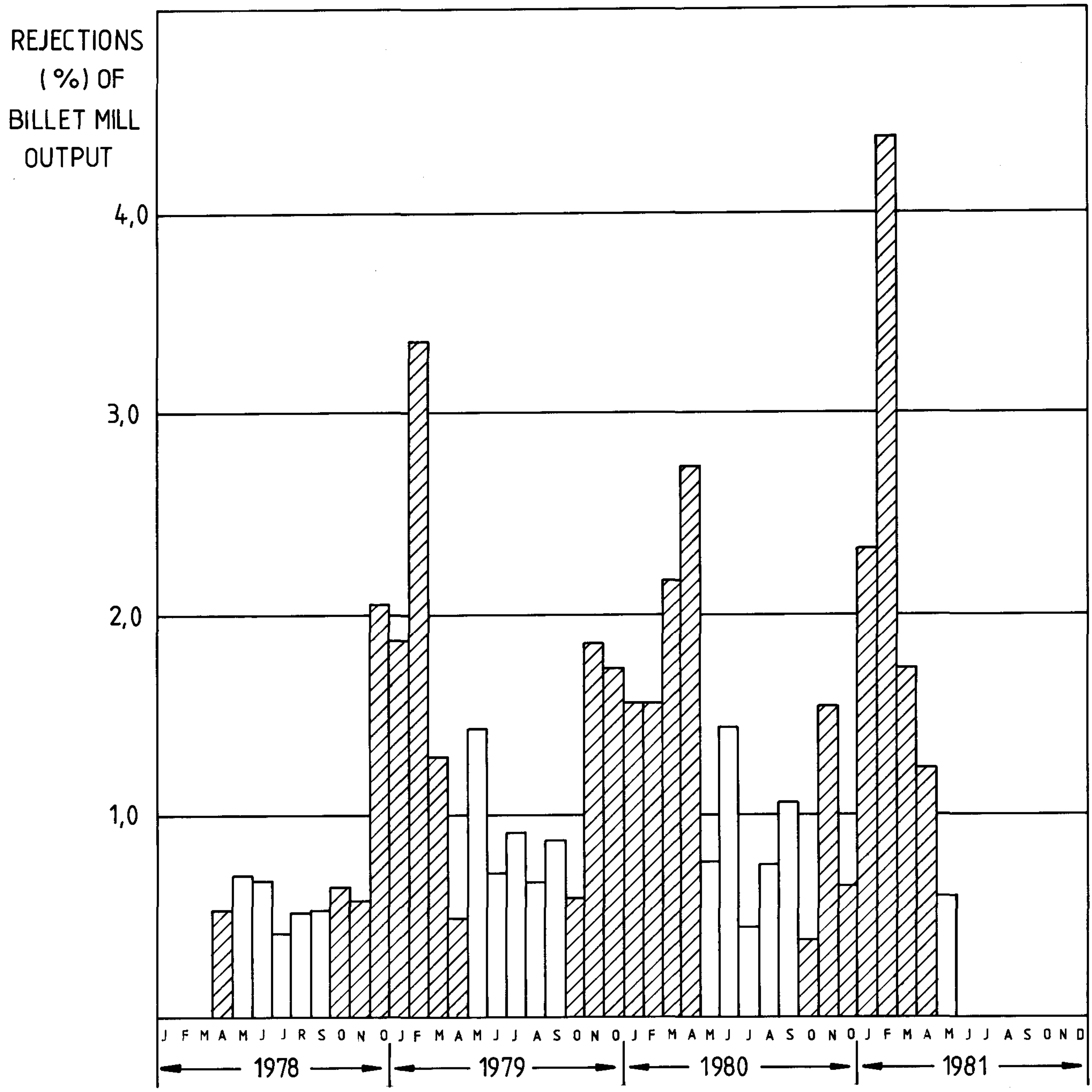

Fig. 2—Rejections because of the torn-corner defect, the shaded months representing the rainy season in the Newcastle area.

TABLE I

AVERAGE INCREASE* OF NITROGEN IN THE STEEL AFFECTED BY REBLOWS AND OPEN-STREAM CASTING

End-point	After 1st reblow	After 2nd reblow	L.A.R.†	Mould
0	15 ± 13	44 ± 17	0	16±11
n = 112		n = 49	n = 62	

* Values given in p.p.m. ±2 standard deviations (2σ). The mean values were treated as true values if the base value was zero.

† Ladle after rinsing.

significant pick-up of nitrogen takes place in the furnace-tapping stream. The same was true for nitrogen rinsing of the ladle.

However, as shown in Fig. 6, there is a relationship between the nitrogen and the carbon levels. This is due to the practice followed in the making of high-carbon grades. Since the major tonnage of these grades is used for the manufacture of rod for use in wire ropes, the phosphorus levels have to be about 0,015 per cent to suppress the formation of martensite while the rod cools. This is achieved in oxidizing slag conditions, which are obtained at low carbon levels; use is made of a technique

Fig. 3—Torn-corner defect in billets laid out for in-line inspection.

in which the carbon is blown to low levels to produce a low phosphorus concentration and then recarburized to the required level. The nitrogen levels in the recarburizer were measured at 1830 p.p.m., which can be seen as a major source of nitrogen.

Hydrogen

A comparison of the moisture and rainfall measurements showed that the moisture in the raw materials came from the rain. However, the alloys were unaffected. Neither the tonnages of rejected material and the rainfall, nor the tonnages of rejected material and the moisture in the raw materials, showed any correlation. However, most rejections occurred when the moisture content of the alloy was at its highest, although the correlation was not always satisfactory for all carbon levels.

Furthermore, when the total was subdivided according to carbon level, the following grouping was found:

Group 1	$C \leqslant 20\%$
Group 2	$0{,}20 < C \leqslant 0{,}60$
Group 3	$0{,}60 < C$.

Fig. 7 gives a block diagram for Group 1, showing the percentage of torn-corner rejections and the moisture content. A clear relationship emerges, although, for the material of higher carbon levels (Groups 2 and 3), it ceased to be significant.

From the results, it was possible to calculate the amount of moisture contributed to the weekly moisture ingress into the steel by each alloy (in milligrams per ton of steel). These figures are given in Table II as weighted average ingress over the period under consideration. The results show further that 72 per cent of all the rejections during the period under consideration fell into Group 1, 7 per cent into Group 2, and 21 per cent into Group 3. The percentages of the total production were 57, 33, and 10 per cent respectively.

Thus, it can be seen that the rejections occurred mainly in the high- and low-carbon steels, as evidenced by the fact that their contributions to the rejections were much higher than could be expected from their respective shares of the production.

Fig. 4—A close-up of a torn-corner defect

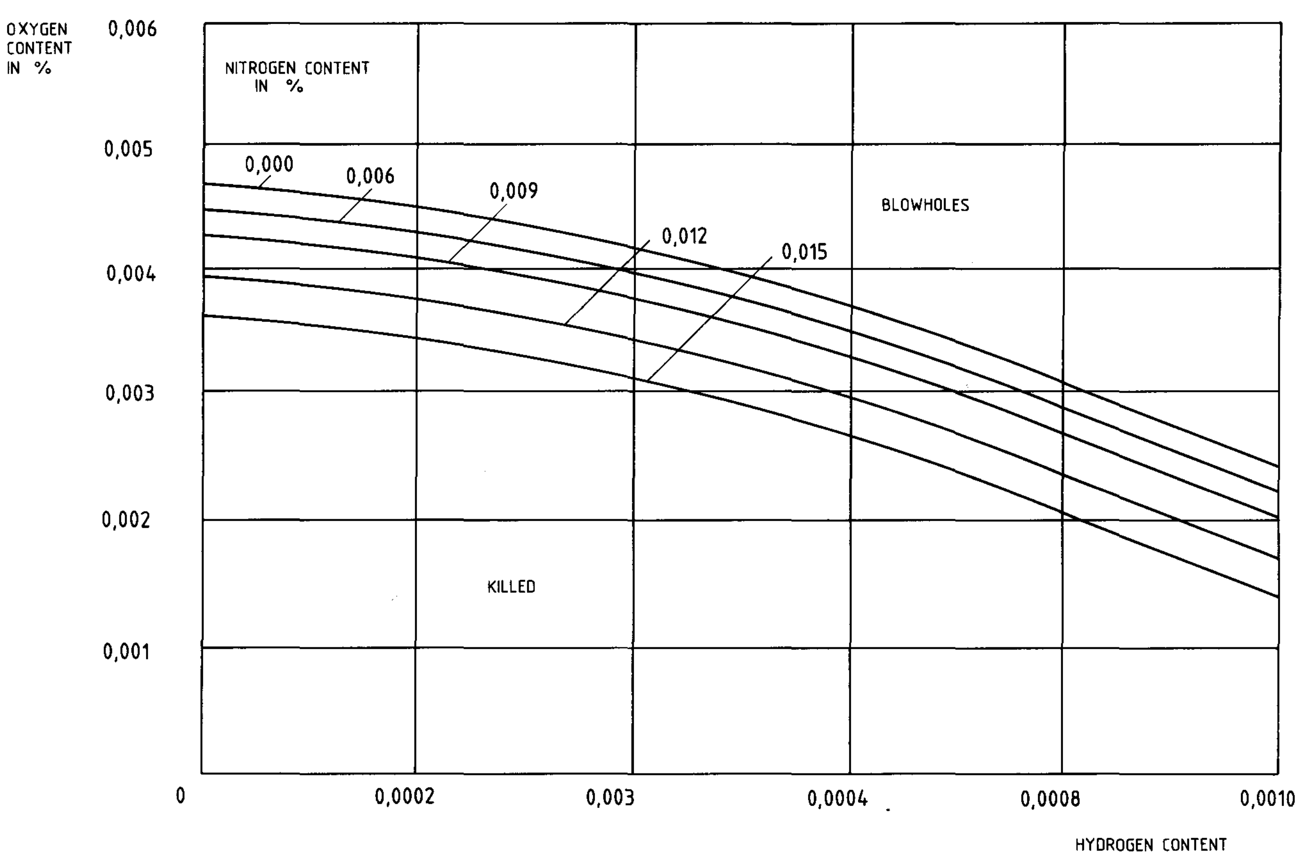

Fig. 5—Influence of nitrogen and hydrogen on the critical oxygen content for the formation of blowholes (after Oeters *et al.*[2])

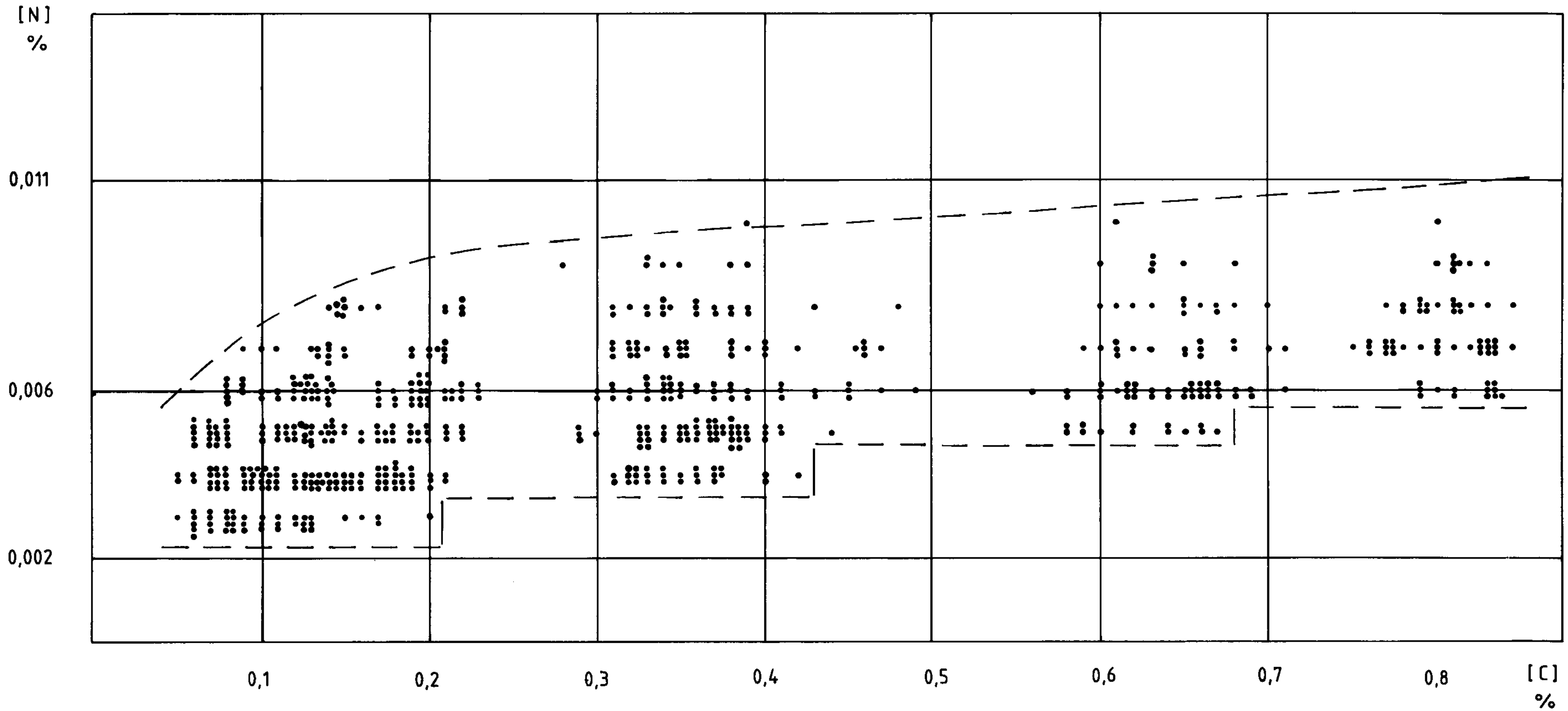

Fig. 6—Dependence of the nitrogen content on the carbon content of the final sample. (Samples were taken from every heat made during the first 2 days of each month in 1981, $n = 632$. Because the reblows were established as one of the major sources of nitrogen pick-up, the plotting of those heats on this graph would have biased the overall picture. Therefore, only the heats without a reblow are shown.)

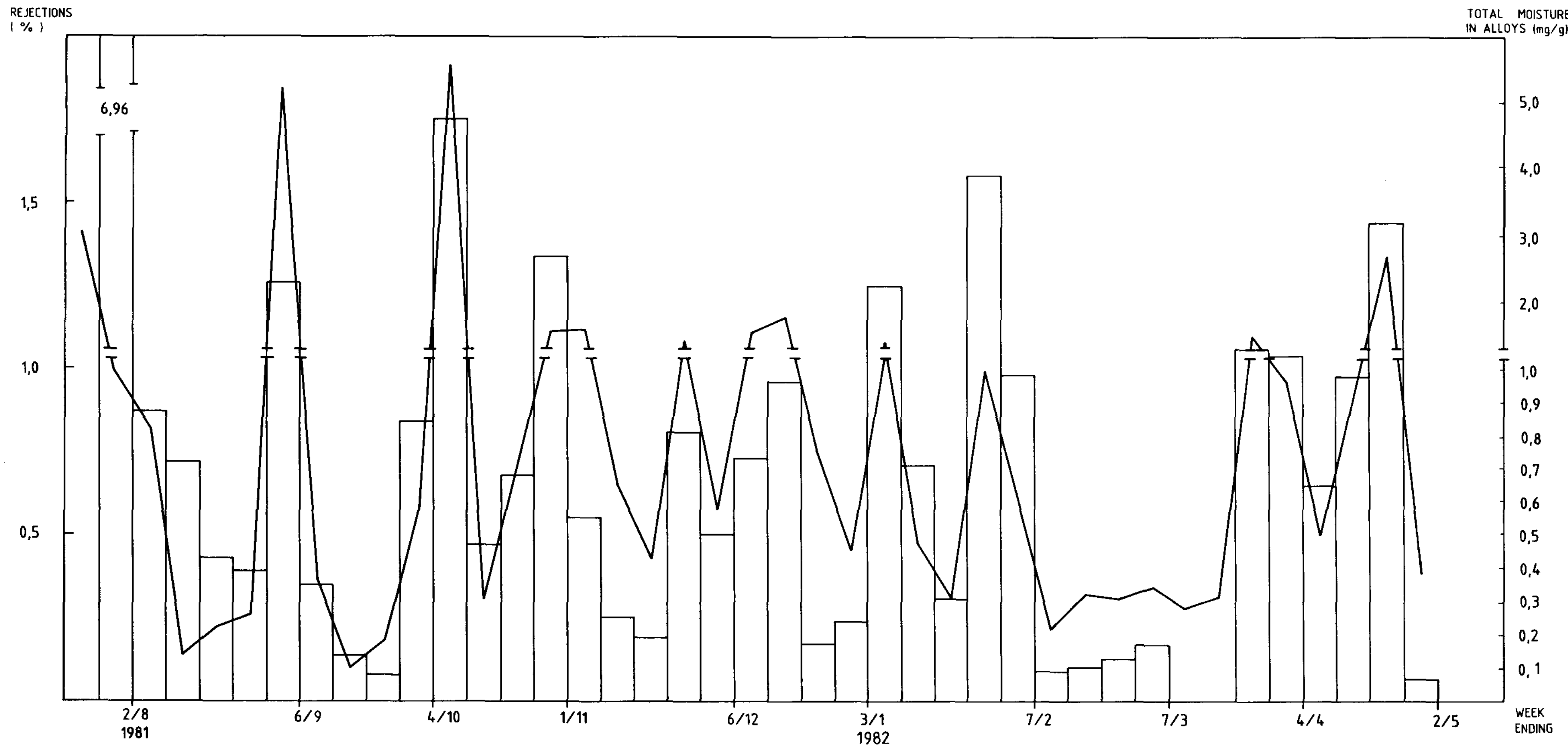

Fig. 7—Torn-corner rejections (block diagram) with the moisture content of the alloys during the period 1/8/81 to 2/5/82. (The carbon range was C $\leqslant$ 0,20 per cent.)

TABLE II

WEIGHTED AVERAGE WEEKLY CONTRIBUTION (IN PERCENTAGES OF THE ALLOYS) TO THE TOTAL MOISTURE INGRESS INTO THE STEEL OVER THE PERIOD 1/8/1981 to 2/5/1982

Alloy	Carbon	HC FeMn	LC FeMn	SiMn	FeSi	Al
Group 1	2,2	50,3	3,1	34,2	5,3	4,9
Group 2	5,9	76,9	0	10,2	5,2	1,8
Group 3	43,6	2,3	0	50,7	3,4	0

Discussion and Conclusions

It is clear that reblowing increases the nitrogen content of the steel. It has been suggested[3] that pick-up is caused by air entering the vessel when it is turned down at end-point; this air is then picked up by the bath when the blowing resumes.

The finding that no significant pick-up of nitrogen takes place in the tapping stream agrees with the findings of Greenberg[4], who suggested that the much lower rate of pick-up results from the surface-active nature of oxygen, which blocks the entry of nitrogen, so acting as a barrier against the pick-up of nitrogen.

Further, that no significant nitrogen pick-up takes place during rinsing, at least not at the rinsing times used in these trials (up to 4 minutes), is believed to be due to a lack of the kinetic conditions required for the conversion of molecular nitrogen to its atomic state in the steel.

As can be seen from Fig. 6, there is a relationship between the carbon and the nitrogen contents of the steel. As stated earlier, the practice at the Works is such that the heat is blown down and then recarburized to the required level. Thus, the final carbon level is a direct reflection of the amount of graphite added and, because the increase in the nitrogen content is tied to the carbon content, it is clear that the bulk of the nitrogen pick-up is from the inherent nitrogen in the graphite. This is not surprising when it is considered that the nitrogen content of the graphite was 1830 p.p.m., which is almost eight times higher than that of the second-richest alloy, high-carbon ferromanganese (230 p.p.m.).

Although no pick-up of nitrogen took place in the tapping stream, the case is different during casting, when the steel is fully killed. A nitrogen pick-up averaging about 0,0016 per cent between the ladle and the mould is seen to be of a normal magnitude for open-stream casting. Similar results have been reported by Koros[5]. Attempts to employ shrouding devices in order, among other things, to reduce the pick-up have generally been unsuccessful mainly owing to the lack of a properly sealed connection between the shroud and the bottom of the ladle or tundish. In some instances, this could even encourage pick-up by ensuring a more intimate mixing in the turbulent conditions of the stream.

The fact that the moisture in the raw materials emanated from the rain was understandable since they are exposed to the elements all the way from their point of origin to the furnace bunkers.

As it was established that rain was not responsible for the moisture in the alloys, the reason had to be sought elsewhere. The source has not yet been established, but the possibilities include a leakage in the system somewhere on the line.

That there is no relation between the moisture content of the raw materials and the incidence of the torn-corner defect is believed to be due to the fact that the hydrogen is purged to a certain extent from the bath during the blow, a common phenomenon with nitrogen. Further, it appears from the results, although this is contrary to the commonly held view, that hydrogen is not picked up by the open-casting streams, not even during periods of high humidity. It is considered that the hydrogen fed into the steel with the alloys is not removed during processing and appears during solidification of the cast strand. Therefore, it is not surprising that there is a good relationship in low-carbon steels between the rejections and the moisture content of the alloys. This is particularly significant when one considers that no corrections were made with respect to the relative consumption of the different alloys, but the moisture contents of each individual alloy were simply added together.

The explanation for the fact that there is little relationship in the higher-carbon steels between the moisture in the alloys and the rejections could be as follows.

Although no measurements were made (because of a lack of suitable equipment), it is believed that the hydrogen content of the higher-carbon steels is lower than that of the lower grades owing to the strong inhibiting effect of carbon on the solubility of hydrogen[6]. Further, as was established earlier, the nitrogen content in the higher-carbon steels was correspondingly greater. It is suggested that the torn-corner defect is caused by the combined effect of the oxygen, hydrogen, and nitrogen. In the low-carbon steels (containing less than 0,20 per cent carbon), the major contribution to the total pressure is made by the partial pressure of hydrogen, and, in the high-carbon steels, by the partial pressure of nitrogen. Fig. 5 clearly demonstrates the combined effect of these three gases.

Researchers disagree about the mechanism involved in the formation of blowholes, and the authors feel it unnecessary to take sides in the argument. However, they suggest that the following occurs in the case under discussion.

A prerequisite for the formation of blowholes is the presence of soluble oxygen in the steel. During solidification, particularly during the formation of the first few millimetres of the rim, when the solidification rate is extremely fast, the oxygen precipitates out of solution to form carbon monoxide if the equilibrium concentration is exceeded. However, the presence of other gases such as nitrogen and hydrogen can greatly influence the carbon–oxygen reaction by reducing the partial pressure of carbon monoxide, at the solidification front and thereby enhancing the carbon–oxygen reaction. (This should be compared with argon in the argon–oxygen decarburization (AOD) process.) Hence, the nitrogen and hydrogen act as major contributors to the formation of blowholes, if not being entirely responsible.

As shown in Table II, in Group 1, where hydrogen was established as the contributor of the defect formation, the main moisture carriers were high-carbon ferromanganese and silicomanganese, together contributing almost 85 per cent of the moisture input per ton of steel. This finding is in perfect agreement with those reported by Schmitz[7].

In Group 2, the same two alloys acted as the main moisture carriers. In Group 3, high-carbon ferromanganese was replaced by graphite, not because there is more moisture in the graphite in this group than in the two others, but because the results were given in milligrams per ton of steel and the results reflect the much larger amount of graphite added to the high-carbon steels. However, for Groups 2 and 3, as was shown earlier, there was no correlation between the moisture content and the torn-corner rejections.

The fact that 72 per cent of all the rejections were among the low-carbon steels (Group 1) and 21 per cent among the high-carbon steels (Group 3) is thought to be due to the high hydrogen and high nitrogen contents respectively. If this is so, a reduction in the amount of hydrogen and nitrogen in the low- and high-carbon steels respectively would reduce the torn-corner rejections. Alternatively, where possible a more-efficient deoxidant could be used.

As far as hydrogen is concerned, the following steps could be taken. Firstly, the exact source of possible water contamination of the alloys could be found, and secondly, the lump size of the ferro-alloys could be increased to eliminate the small fractions, which always contain the bulk of the moisture[7]. If the above action does not produce satisfactory results, steps could be taken to dry out the high-carbon ferromanganese and the silicomanganese, which were the main moisture carriers.

As regards nitrogen, it has been found very difficult to decrease the reblow ratio, but the situation may be different when the planned ladle-injection plant comes on-stream. The availability of such a unit may facilitate the transfer of at least some of the reblowing for sulphur and phosphorus to the injection unit. A further possibility is the introduction of low-nitrogen graphite for recarburizing, and the incorporation of effective ladle and tundish shrouding for the high-carbon steels.

When the remedies suggested above were considered, in conjunction with the senior management of the Works, against the long-term plans for the steelplant, it was decided that single solutions of this kind should be avoided. Although they would have solved the problem for the time being, they would become obsolete within a few years, when the long-term plan was implemented.

It was therefore decided that the equipping of the basic oxygen furnaces with a gas-rinsing facility according to the long-term plan, together with effective ladle and tundish shrouding at the continuous casting, would offer the best overall solution for the steelplant. In addition to the well-documented advantages of gas-rinsing of the bath during the furnace blow (such as improved iron yield and desulphurization, faster scrap melting, and less tendency to slop), gas-rinsing would result in a high degree of dephosphorization without over-oxidizing slag conditions at low carbon levels as prevailed at the time of the investigation. The 'catch carbon' blowing procedure could be practised, which would eliminate the need for recarburization. Not only would this result in considerable savings, but it would end the pick-up of nitrogen from the graphite, which had been established as the major source of nitrogen in the steel.

Further, the gas-rinsing practice would reduce the manganese losses during the furnace blow, and would therefore diminish the need for the charging of ferromanganese and silicomanganese into the steel during tapping, so avoiding the pick-up of hydrogen, these two alloys being the two major hydrogen carriers.

The low gas contents of the steel thus attained at the basic oxygen furnaces would be further maintained by effective ladle and tundish shrouding.

The work has been continuing along the lines recounted above, and the results are encouraging and confirm the expectations. The authors hope to publish a full report of the achievements at a later date.

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References

1. Turkdogan, E. T. Causes and effects of deoxidation occurring during cooling and solidification of steel. *Trans. Metall. Soc.* AIME, vol. 233. Dec. 1965. pp. 2100–2112.
2. Oeters, F., *et al.* Zur theorie der metallurgischen vorgänge bei der eerstarrung von stahl. *Archiv Eisenhuttenwese*, vol. 40. 1969. pp. 603–613.
3. Pehkle, R. D., *et al. BOF steelmaking.* Warrendale (U.S.A.), AIME, 1974. vol. 1, 119 pp.
4. Greenberg, L. A., *et al.* Nitrogen pick-up in low-sulphur steel. *Ironmaking and Steelmaking*, vol. 9, no. 2. 1982. pp. 58–63.
5. Koros, P. J., *et al.* Effect of steelmaking and deoxidation variables on the nitrogen content of BOF steel. *AIME Open Hearth Proceedings*, vol. 53. 1970. pp. 97–107.
6. Weinstein, M., *et al.* Solubility of hydrogen in liquid iron alloys. *Trans. Metall. Soc. AIME*, vol. 227. Apr. 1963. pp. 382–393.
7. Schmitz, K. H., *et al.* Untersuchung der Einwirkung von Wasser auf ausgesuchte Ferrolegierungen. *Stahl und Eisen*, vol. 101, no. 4. 1981. pp. 49–53.