

DEOXIDATION AND INCLUSION CONTROL FOR ALLOY STEEL

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DEOXIDATION of quality steels is directed toward the casting of sound ingots free from excessive segregation, having good rolling and forging characteristics, and containing a minimum of harmful impurity elements and inclusions. In addition, deoxidation is employed for grain size control to promote maximum toughness of the steel. These objectives are achieved by selection of suitable charge material, slag control and initial deoxidation practice in the furnace, and final deoxidation practice in the ladle. Although much has been learned of the physical chemistry of the process, the art of steel-making is still in large part empirical, and successful practices are somewhat difficult to rationalize. For this reason, equilibrium relations in the iron-oxygen deoxidizer systems are important, but the kinetics of deoxidation and the sequence of operations may be more significant to the operator.

Inclusions in steel are primarily oxides and sulfides formed during cooling from the residual oxygen and sulfur remaining after slag treatment and the addition of elements designed to limit their solubility. Although other elements, such as nitrogen, selenium, etc., may on occasion be present in inclusions, they are of such limited significance that they have been disregarded in this discussion. Similarly, exogenous inclusions resulting from entrainment of slag and refractories, although present in all steels, will be treated separately, even though in practice they react chemically with the metal.

Oxygen Solubility and Inclusion Formation

Alloys of iron with deoxidizing elements and oxygen have been studied to determine

the solubility of oxygen in the molten metal as summarized in Fig. 1¹. Certain combinations of deoxidizers form complex oxides with less solubility than the simple oxides, notably manganese with silicon or aluminum as shown in Fig. 2. Effective deoxidation for killed steels depends on addition of sufficient

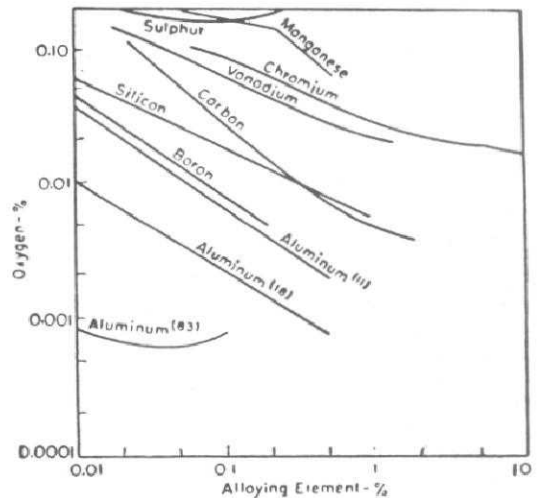


FIG. 1 — EFFECT OF VARIOUS ELEMENTS ON THE SOLUBILITY OF OXYGEN IN MOLTEN IRON AT 1600°C. (CARNEY¹)

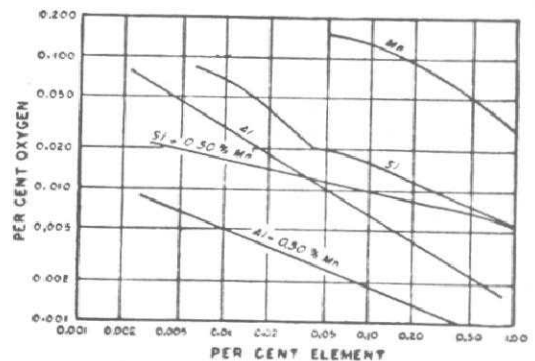


FIG. 2 — EFFECT OF MANGANESE ON DEOXIDIZING POWER OF SILICON AND ALUMINUM (HILTY AND CRAFTS²)

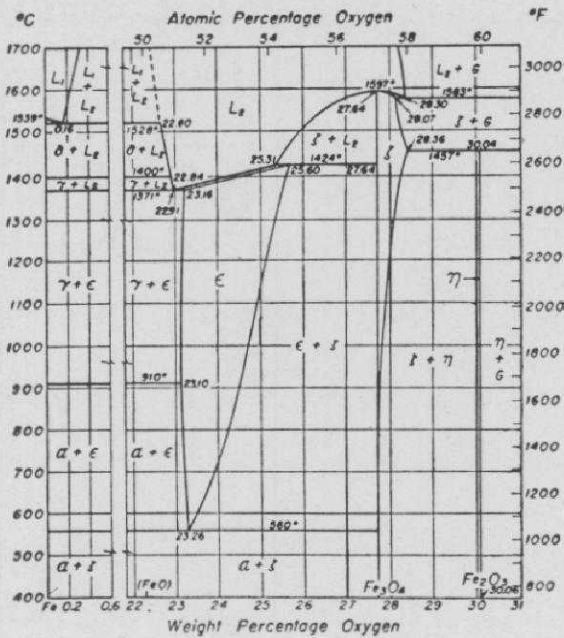


FIG. 3 — Fe-O DIAGRAM (DARKEN AND GURRY³)

deoxidizer to lower the oxygen content below the amount that will react with carbon.

The iron-oxygen system, Fig. 3, contains a liquid miscibility gap which is expanded by the deoxidizing element. Not only is the solubility in the liquid metal phase restricted, but the melting temperature of the oxide phase is also usually raised. Thus, during cooling and solidification the oxides may be rejected as solid particles rather than as a liquid slag phase with corresponding changes in the inclusions.

The iron-sulfur system, Fig. 4, on the other hand, does not have a liquid miscibility gap,

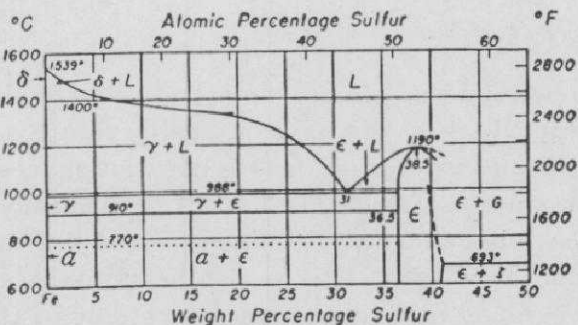


FIG. 4 — Fe-FeS DIAGRAM (CHIPMAN⁴)

and solidification is by a simple eutectic mechanism. Although deoxidizing elements may introduce a miscibility gap, the solubility of sulfur in the liquid at 1600°C. is seldom limited to such a degree that the metal is effectively desulfurized. Thus, the iron-sulfur-oxygen system contains, Fig. 5, a miscibility gap extending from the metal-oxygen side into the diagram. The inclu-

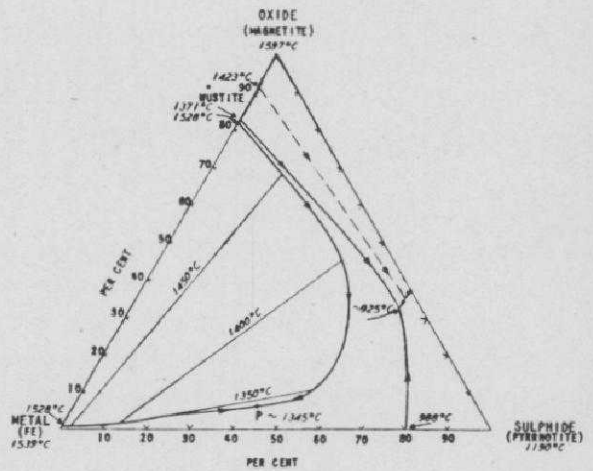


FIG. 5 — Fe-O-S DIAGRAM (HILTY AND CRAFTS⁵)

sions formed during solidification depend mainly on the oxygen-sulfur ratio. A high oxygen-sulfur ratio, Fig. 6, produces globular particles of oxide or mixtures of oxide and sulfides. At higher sulfur-oxygen ratios the globular oxide may disappear and intergranular sulfide inclusions will predominate as in Fig. 7.

As illustrated schematically by Fig. 8, the introduction of more than about 0.3 per cent manganese in the liquid metal profoundly modifies the iron-sulfur-oxygen diagram. A metal-sulfide miscibility gap extends into the system and joins the metal-oxide gap. Because the melting points of the oxide and sulfide phases now exceed that of the metal, the metal-oxide and metal-sulfide eutectics are shifted so that they originate in the metal corner of the diagram, intersect the miscibility gaps, and continue on the other

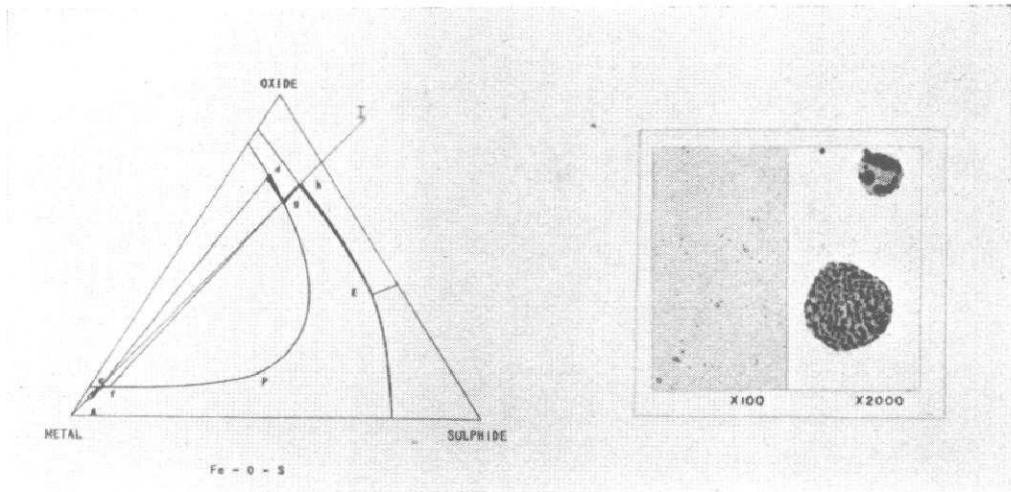


FIG. 6 — FORMATION OF INCLUSIONS IN Fe-O-S SYSTEM AT HIGH OXYGEN-SULFUR RATIO (CRAFTS AND HILTY⁶)

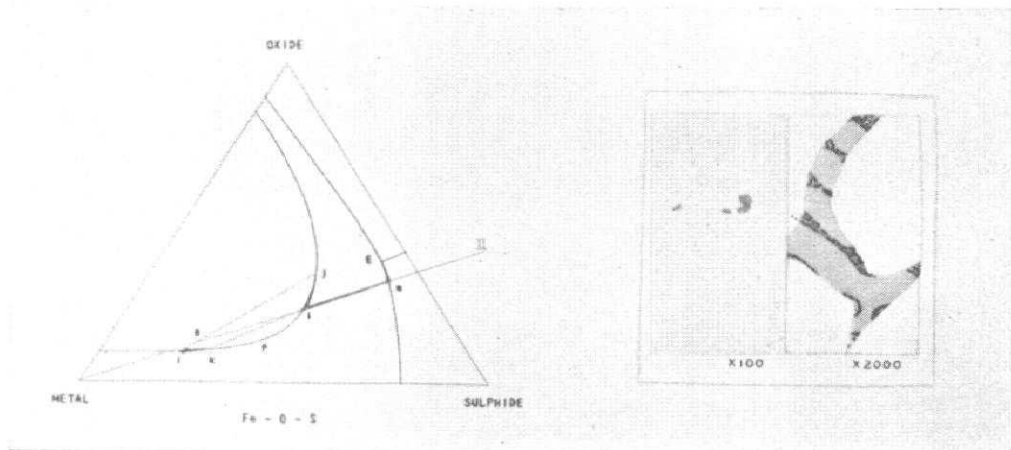


FIG. 7 — FORMATION OF INCLUSIONS IN Fe-O-S SYSTEM AT LOW OXYGEN-SULFUR RATIO (CRAFTS AND HILTY⁶)

side to the ternary eutectic that is in the same relative location as in the basic system.

Inclusion formation in the modified system, however, is still controlled primarily by the oxygen-sulfur ratio. At very high ratios, Fig. 9, the inclusions are primary oxide crystals analogous to those formed by de-

oxidation with aluminium and globular oxides formed when the oxide miscibility gap was encountered during the solidification process. At intermediate ratios, Fig. 10, the inclusions are predominantly globular in nature and may be duplex types rich either in oxide or in sulfide depending upon which side of the ternary eutectic ratio they originate. Some

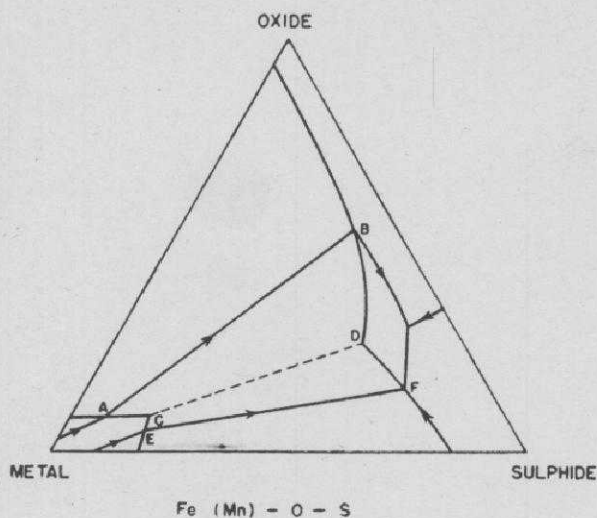


FIG. 8 — SCHEMATIC Fe(Mn)-S-O DIAGRAM (Mn 0.3 PER CENT IN LIQUID METAL) (HILTY AND CRAFTS⁷)

intergranular inclusions may also occur although the tendency in this direction is limited, being maximum when the oxygen-sulfur ratio approaches that of the ternary eutectic or the intersection of the miscibility gaps. If the oxygen content is very low and the sulfur content quite high, so that the system is saturated with sulfide rather than oxide, primary sulfide crystals as well as

globular sulfides may be observed. Such a condition rarely occurs in practice and is mainly of academic interest.

Although the diagram in Fig. 8 may have direct application in the case of free-machining steels, its major significance lies in its implications with regard to the mechanism of inclusion formation in general. It demonstrates that intergranular inclusions are minimized if the non-metallic matter is rejected or precipitated early during the solidification process, as occurs when the solidification path is interrupted by a miscibility gap. The great virtue of manganese is its introduction of such a miscibility gap between the metal and sulfide phases. Manganese is the only one of the common deoxidizing elements that does this in the concentrations ordinarily used in steel-making. The diagram also indicates that the objectionable oxide segregates resulting from primary precipitation of oxide crystals may be reduced in quantity if excessively high oxygen-sulfur ratios are avoided.

The diagram for the manganese modification of the iron-sulfur-oxygen system has been established experimentally⁷. By inference from this diagram and the appearance

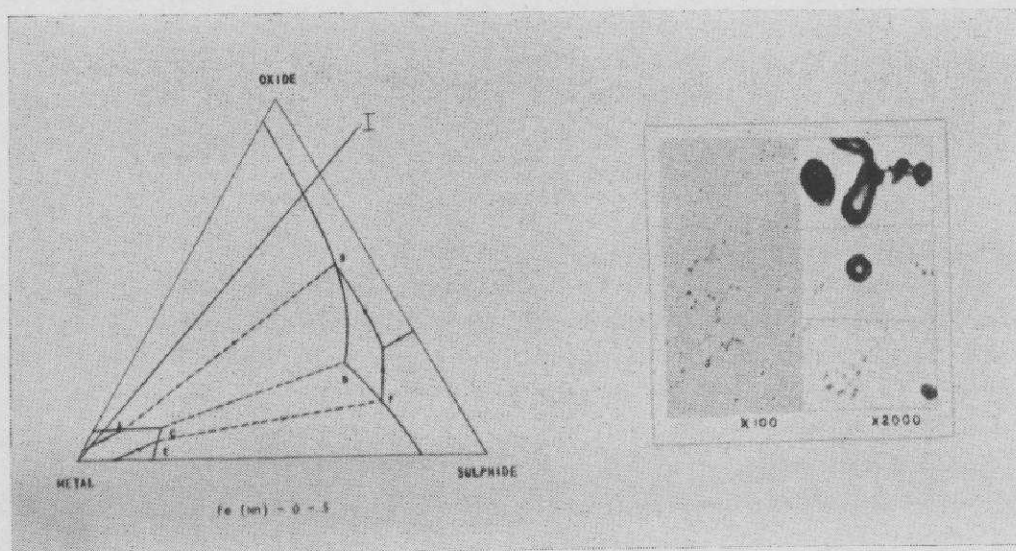


FIG. 9 — EFFECT OF HIGH OXYGEN-SULFUR RATIO ON INCLUSIONS IN Fe(Mn)-S-O SYSTEM (CRAFTS AND HILTY⁸)

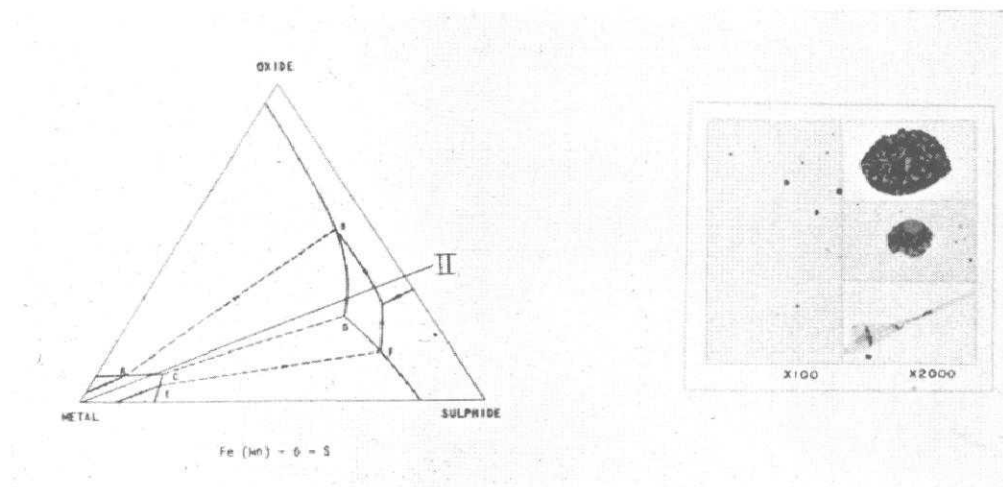


FIG. 10 — EFFECT OF INTERMEDIATE OXYGEN-SULFUR RATIO ON INCLUSIONS IN Fe(Mn)-S-O SYSTEM (CRAFTS AND HILTY⁶)

of inclusions, similar diagrams for modifications of the basic system by other deoxidizers or combinations of deoxidizers have been proposed⁶. All such diagrams refer to equilibrium conditions. Moreover, they imply that if the compositions of two melts are the same at the time solidification begins, then the solidification processes and the inclusions will be similar no matter how the original starting compositions were attained. Practically, however, the same final composition is apparently reached by different solidification patterns resulting in different inclusions, so that some extra-equilibrium condition must be responsible.

Effect of Initial Oxygen Content

The variable in a heat of steel that is most influenced by furnace practice is the initial oxygen content, that is, the oxygen content of the metal in the furnace prior to tap and the final deoxidizer addition. It is affected by the carbon content, the boiling action, the slag condition, the furnace atmosphere, the degree of initial deoxidation, and a variety of other factors. On the other hand, the

final oxygen content of the metal in the molds at the time solidification begins is established only by the final deoxidation, and, as demonstrated by Tenenbaum and Brown⁸, it bears no relation to the initial deoxidation or previous condition of the heat. Nevertheless, for steels of the same final composition including alloys and deoxidizers, the net effect of variations in furnace practice, that is initial oxygen content, on the inclusion types after solidification, is the same as would be predicted from the solidification diagrams as if there actually were differences in the final oxygen-sulfur ratios of the steels.

As described in an earlier paper⁶, the extra-equilibrium factor involved may be a type of nucleation phenomenon resulting from retention by the metal of nuclei representative of a previous stage in the oxidation or deoxidation of the heat. It is emphasized, however, that this hypothesis does not presume the existence of substantial quantities of non-metallic inclusions suspended in the liquid metal. Chemical and microscopic investigations have demonstrated that the bulk of deoxidation products separates from the

metal with great rapidity so that such a presumption would be without foundation, and, in fact, would be in contradiction to the evidence. On the other hand, the evidence does not preclude the presence of a large number of nuclei. The smallest particle that can be resolved by the light microscope is of the order of 0.2 micron in diameter. According to Stokes' law, particles smaller than this would remain in the liquid metal indefinitely. Moreover, concentrations as high as 0.001 per cent would be quite difficult to determine accurately by chemical analysis. Assuming the average diameter of the particles to be half the diameter of the largest, it can be calculated that a cubic inch of steel containing 0.001 per cent of them would contain approximately 10^{12} particles.

It is further emphasized that this postulate refers to nucleation of a solidification pattern rather than specific kinds of oxides or sulfides. For example, steel initially deoxidized with silicon prior to final deoxidation with $1\frac{1}{2}$ lb. or 2 lb. per ton of aluminum does not contain silicate inclusions. On the other hand, a heat that has been initially deoxidized has less of a tendency toward oxide type inclusions than one that has not, in spite of the fact that the final oxygen contents may be the same. Moreover, the tendency is less in a heat initially deoxidized with silicon and manganese rather than with silicon alone, presumably because the initial oxygen content is lower. Similarly, a heat worked to a low carbon content and then recarburized in the ladle contains more oxide inclusions for a given final oxygen content than if the same heat were tapped at the desired carbon content. According to the nucleation hypothesis, then, the solidification pattern may be established by the initial oxygen content, with the specific inclusion types being modified by the final deoxidation treatment. Furnace practices affecting the initial oxygen content before tapping and final deoxidation are, therefore, critical.

Control of Initial Oxygen

Although the mechanism by which initial oxygen content affects quality is not well understood, the effects of steel-making practices that control initial oxygen are quite apparent not only in the inclusions themselves, but in soundness as revealed by deep etching and by hot-shortness in rolling. With respect to inclusions the low-carbon steels are relatively more dirty than would be anticipated. Further, the inclusions are related not to the final carbon content of the steel, but to the minimum carbon that was reached prior to killing and recarburizing. This is very pronounced in rail steel made by heavy recarburizing additions. Steels in which large amounts of high-carbon ferro-manganese are used instead of silico-manganese or low-carbon ferro-manganese are relatively dirty. This tendency is more pronounced below 0.30 per cent carbon and accounts for the common use of silico-manganese for initial deoxidation or 'blocking' in the lower carbon open-hearth steels. Free-machining high-sulfur steel similarly contains the desirable dispersed sulfide inclusions if the carbon content is taken no lower than is necessary to add low carbon content ferro-manganese. Another type of example is the increased yield of good product after strong initial deoxidation. This was shown by Silliman and Forsyth⁹ and is illustrated in Fig. 11 by the extra conditioning that was necessary with less effective initial deoxidation.

In considering the oxygen content in the manufacture of steel, it is necessary to modify the analogy with the carbon-free oxygen-sulfur-iron-deoxidizer systems because of the effect of carbon monoxide partial pressures on the carbon-bearing system. Larsen¹⁰ found that the oxygen content of open-hearth steel was about 25-40 per cent higher than the equilibrium amount of oxygen. As shown in Fig. 12, Carney gave similar data for other steel-making practices. Larsen found that this super-equilibrium or 'delta'

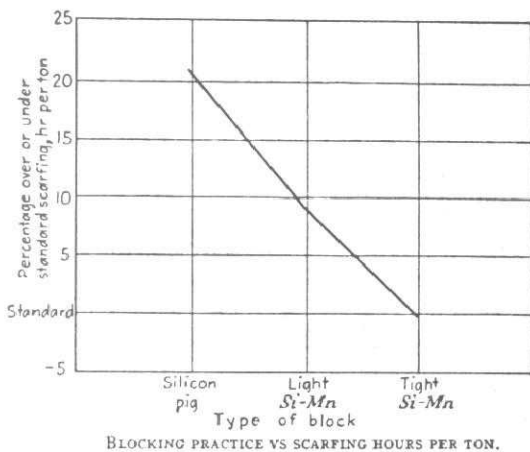


FIG. 11 — EFFECT OF BLOCKING ON CONDITIONING COSTS (SILLIMAN AND FORSYTH⁹)

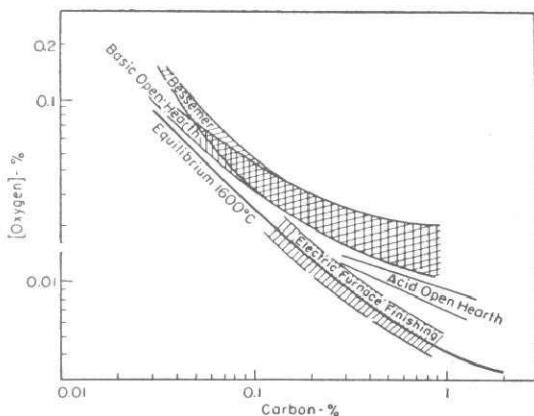


FIG. 12 — VARIATION OF OXYGEN CONTENT OF MOLTEN STEEL WITH CARBON CONTENT IN VARIOUS STEEL-MAKING PROCESSES (CARNEY²¹)

oxygen could be lowered somewhat by an active boil. Tenenbaum and Brown demonstrated that delta oxygen could be minimized by initial deoxidation in the open-hearth furnace. Marsh¹¹ found that equilibrium oxygen contents could be reached under reducing slags in arc furnaces.

The control of oxygen in the arc furnace is, of course, much more readily achieved than in the open-hearth furnace. Marsh found that oxygen contents comparable to those usually observed in open-hearth practice

were present at the end of the carbon boil. However, very soon after the slag was made reducing in character, the oxygen content dropped to the equilibrium level. Long holding beyond 15-30 minutes produced no further drop in oxygen content, so that protracted 'cooking' was not beneficial with respect to oxygen. Furthermore, a somewhat similar condition has been found to control the elimination of sulfur. Urban and Derge¹² were unable to remove sulfur when the silicon content of the metal was low, and Shulz¹³, Reagan¹⁴ and Bigge¹⁵ found that sulfur removal was promoted by a silicon content in the metal. Fondersmith¹⁶ indicated that high manganese acted in a similar way and unpublished reports that aluminum is effective suggest that the mechanism is similar to that proposed¹⁷ for pig iron and high-carbon alloys; namely that a deoxidizer must be present to react with the oxygen that is freed when iron sulfide reacts with the oxide of the slag.

In the basic open-hearth furnace the control of oxygen and sulfur is more difficult because of reaction with furnace gases and because the slag is designed primarily for oxidation of a high-carbon, silicon, and high-phosphorus charge. Low sulfur is essentially a matter of low-sulfur fuel with some control of the partition ratio between slag and metal. A high base-acid ratio¹⁸, a low iron-oxide content¹⁹, and a low MgO content²⁰ are helpful.

In his studies of oxygen content of open-hearth steel, Larsen found that 'delta' oxygen varied somewhat with the FeO content of the slag, and that the total residual oxygen at tap was controlled by temperature, boiling action, final ore addition, and carbon content. In addition to studies of initial oxygen content, extensive reports of practices designed to give high quality have been made by furnace operators in the Proceedings of the Open-Hearth Conference, A.I.M.E. These reports have been reviewed with respect to slag practice and initial deoxidation or blocking practice.

There is agreement that the heat should melt at least 0.50 per cent carbon above the tap carbon, and that soft or close melts are undesirable. A deficiency of charge limestone also appears desirable for fast melting and rapid attainment of temperature. Burned lime is preferably added gradually, as are ore additions, in such a way as to maintain consistently a uniform boiling condition. Late ore additions are generally deplored, and it is usually recommended that the slag be shaped up, and tapping temperature attained at least 45 minutes before tap. The maintenance of a long and continuous boil, at such a rate that temperature is reached before the carbon drops too low, is considered to be essential, and graduated lime, ore, or spiegel reboiling additions are generally recommended. These conditions are conducive to relatively low (8-14 per cent) FeO in the slag, and relatively high residual manganese in the metal. These factors are generally conceded to be helpful. There is a general preference for temperatures to be relatively hot, but not excessively so, and a light skull is acceptable to some operators. There is real divergence in opinion on the desirable degree of basicity. Some prefer a creamy slag with a lime-silica ratio in the neighbourhood of 2.5 to 1, whereas others prefer a heavy but not viscous slag with a ratio of about 3 to 1 or higher. It is notable that the shops that prefer the more highly basic slags are usually located in areas where sulfur is more of a problem, and it is suspected that they are forced to make a compromise with the preferred practice in order to lower sulfur.

The general pattern of this lean slag practice is quite well established and generally accepted for quality steel. Its main features appear to be rapid and early attainment of high temperature, a long and uniform boiling period, a relatively high residual manganese, and a relatively low FeO content in the slag. These features have been correlated with improved quality, but, so far as is known,

do not have any effect on the oxygen content at the end of the working period.

Blocking or initial deoxidation in the furnace prior to tapping was initiated in order to stop the carbon drop until the metal could be analysed prior to final additions. It was observed that under some conditions the block also produced an improvement in quality. Now, with more rapid analytical methods, the block is not so necessary to control chemical composition, and is primarily used to benefit quality. There is no agreement regarding whether blocking is desirable, and the nature of the controversy is illustrated by the discussion initiated by Philbrook in the Open Hearth Conference of 1947. Most of the statements regarding blocking practice are unsubstantiated by sufficient data to serve as a basis for judgement, and a few of the better illustrated cases will be described.

Silliman and Forsyth reported the effect of different blocking practices on high-sulfur steels, as shown above. On the other hand, Flaherty, discussing similar steels at the 1953 Open Hearth Conference, reported that heats tapped open with no block gave more consistent chemical analysis, and had better surface as compared with blocked heats. Gelder in 1949 reported that a statistical study of the internal cleanliness on sheared blanks of 1025 cartridge case steel demonstrated an improved condition resulting from a blocking treatment of spiegel, silico-manganese and ferro-manganese added at graduated intervals in the furnace. Todd amplified Gelder's statement with respect to the advantage of a tight block. Huhn in 1953 reported the use of pig iron for high-carbon steel, a light silico-manganese block for lower carbon steels which did not have rigid density (deep etch) requirements, and a heavy silico-manganese block for high-density specifications.

The manner in which blocking agents are used is informative. It is common to use light blocks or no block on high-carbon (over 0.50 per cent) steels. Silicon pig, spiegel

and even pig iron seem to be adequate for these steels. If the heat is very hot, silico-manganese is more effective. In lower carbon grades most of those reporting used silico-manganese. It is common practice to use about 15 to 20 lb. per ton for a normal block and up to 40 lb. per ton for a heavy block. In medium (0.30/0.50 per cent carbon) steels treated with the usual light block there is only a slight tendency for the silicon to be oxidized to such a degree that the heat opens up and a reboil is initiated. With lower carbon steels the conditions may be more oxidizing, especially if the lean slag practice is not followed, and oxidation of carbon and alloys may start before the heat is tapped. This results in erratic alloy recovery and also a reversion to a dirty condition. The adverse effects of opening a block so that a boil starts have been cited by Belding and Fleming at the Open Hearth Conference in 1946.

In the authors' experience, the reopening of a block to a reboil is a most effective means of making a dirty steel. Such a condition can be made worse only by a bottom boil and a low temperature. It is felt that this is the main reason for failure to obtain benefit from the initial deoxidation. In some respects this viewpoint was confirmed by Tenenbaum in 1952, who expressed the opinion that blocking compensates for the condition caused by incomplete shaping up of the slag in some heats, and thereby guarantees a degree of uniformity in the practice. It is considered that failure to benefit from initial deoxidation can usually be related to some specific cause. The general utility of the blocking practice is evidenced by the observation that of the statements noted in the Open Hearth Proceedings five-sixths of the reports indicated that significant benefits were being realized.

Final Deoxidation

The slag practice and initial deoxidation control the amount of inclusions, but the

final deoxidation and sulfur content, as outlined in Fig. 13, determine the types of inclusions. Although these diagrams are schematic, the inclusion characteristics of common deoxidation practices are quite apparent. In the most simple treatment of killed quality steel, that is one treated with manganese and silicon, but not aluminum, it is evident that the broad ranges of the miscibility gaps suggest that globular oxides and sulfides would be expected within a large bracket of oxygen-sulfur ratios. This is a condition that is typical for acid steel and basic steel castings that are not treated with aluminum. It results in high ductility, but may not be entirely effective in eliminating porosity.

When aluminum is added to a manganese-silicon steel, as is necessary for soundness in modern steel foundry practice and for grain refinement in wrought steels, it is apparent that the amount of aluminum has a controlling effect on the inclusion types. If a large amount (0.05 per cent and up) is added, the inclusions are predominantly oxides with a tendency toward intergranular sulfides at high sulfur-oxygen ratios. The oxides are of the aluminum-oxide type with a fairly high solubility for sulfide. This system is very complex and alternative locations for the metal-sulfide eutectic are shown.

With somewhat less aluminum the oxide phase is probably a low-melting aluminum silicate, and it is difficult to avoid intergranular inclusions. For this reason, the intermediate aluminum additions are seldom used.

Other deoxidizers have not been studied sufficiently to generalize their influence. Titanium and zirconium are somewhat like aluminum, but vary in that the critical oxygen-sulfur ratio, where the change from predominant random oxides to predominant intergranular sulfides seems to occur for the same oxygen content at a sulfur content that, relative to aluminum, is somewhat lower for titanium and somewhat higher for zirconium.

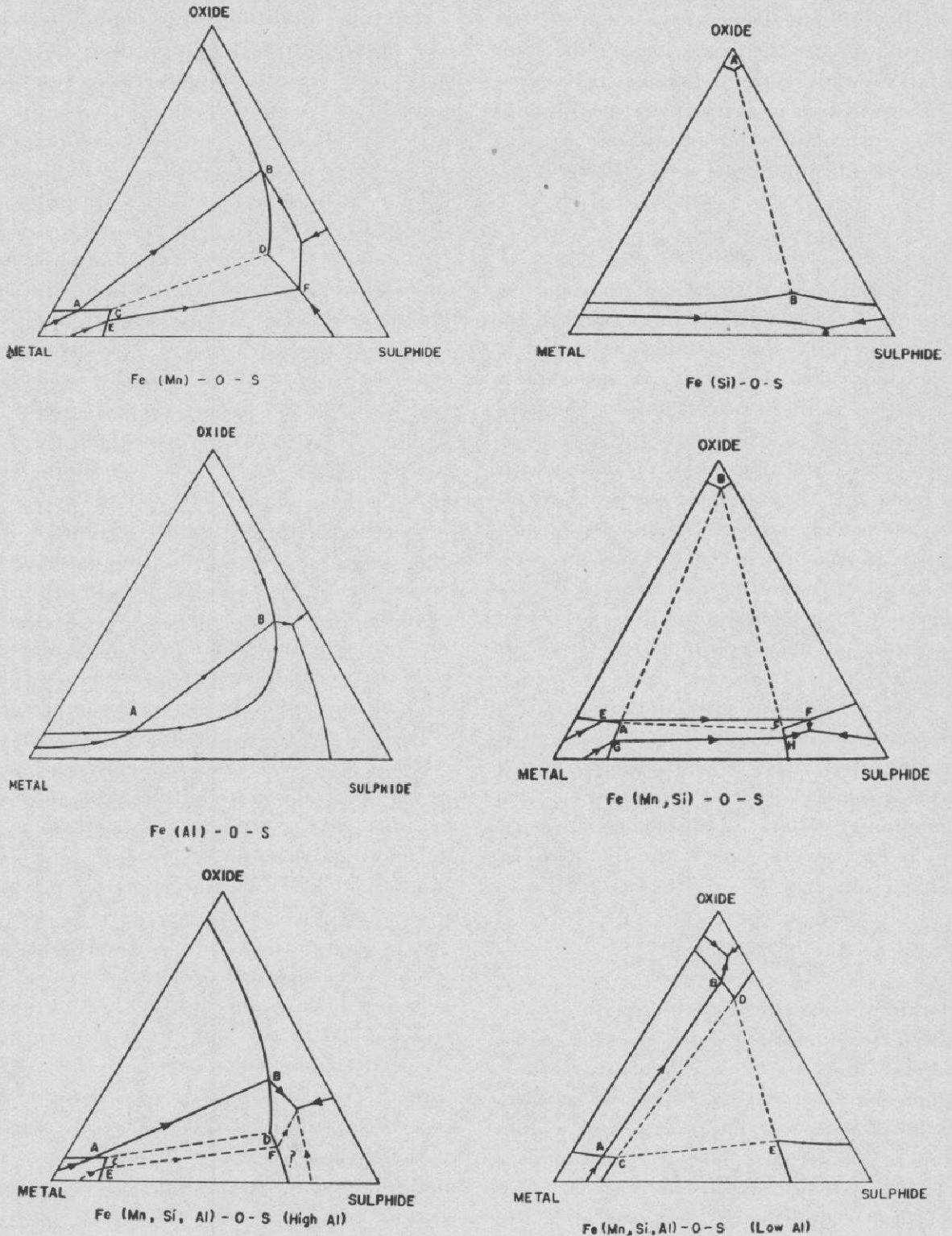


FIG. 13 — SCHEMATIC SOLIDIFICATION DIAGRAMS FOR VARIOUS DEOXIDATION SYSTEMS

Calcium tends to limit sulfide solubility and may actually lower sulfur materially²¹. This tendency seems to persist in much the

same manner as initial deoxidation so that calcium-treated steel castings have a higher tolerance for sulfur. Usually, calcium is

used to promote general cleanliness, but seems to promote the formation of more complex oxy-sulfide types of inclusions. Vanadium also is used in castings and heavy forgings as it promotes fine grain size without a very significant effect on inclusions.

Refractory Inclusions

In tapping steel it is difficult to avoid entrainment of slag with the metal, and in the runner and ladle some refractory is melted. These materials float out rather rapidly unless the metal is quite cold. They do, however, tend to react with the metal and under some conditions may be carried into the mold. If they are trapped in the metal, they are usually large and seriously harmful to tools in machining. Rait²² has discussed the nature of the refractory reactions and has suggested that high-aluminum brick would be helpful. This is particularly important in runners for bottom cast ingots. The rate of pouring from the ladle and the shape of the ladle bottom influence the degree of scouring that may be encountered. Ordinarily, virtually all of the refractory material is eliminated before solidification, unless the heat is excessively cold or the metal is particularly sluggish.

Grain Refinement

Grain refinement with aluminum is normally carried out on a wide variety of carbon and low-alloy steels in order to achieve a higher degree of toughness, greater uniformity in response to hardening, and a minimum of distortion. The deoxidation practices required to develop fine grain size have been well established²³. In general, a residual aluminum content of about 0.03 per cent aluminum is necessary, and the addition required to obtain this residual varies between 0.05 and 0.15 per cent. Low-carbon steels and hot heats require the larger additions.

Aluminum additions are commonly made to structural steels to lower their notched-bar impact transition temperature for low-temperature service. In addition to its effect on grain refinement, aluminum appears to have some toughening effect as an alloying element. These characteristics were summarized in a symposium at the National Bureau of Standards²⁴. The benefit of high-aluminum additions was illustrated by Crafts and Offenhauer in that symposium in reference to chromium-copper-nickel steel that has been fabricated without difficulty and used successfully in chemical reaction vessels at -100°C . for twenty years. This steel is currently being made with aluminum contents in the range of 0.05 to 0.25 per cent. In making steels with higher residual aluminum than is required for grain refinement, especially in steel castings, it is desirable to avoid high-nitrogen contents. The combination of high aluminum and high nitrogen leads to intergranular precipitation of aluminum nitride and the coarse intergranular weakness called 'rock candy' fracture²⁵.

The major use of grain refinement has been in the low-alloy automotive type of heat-treating steel. After the initial work by McQuaid and Ehn on carburizing steels, the practice spread to water and oil-quenching grades until it is now part of the normal specification in the U.S.A. Grain refinement has not received such general acceptance in the United Kingdom and on the Continent. This has led to two quite different methods of specifying low-alloy steels.

In the British system, a composition with very broad ranges is specified to be capable of developing a given tensile strength and minimum impact strength in a given 'ruling' section. The specified tensile strength of each grade of steel is graduated downward as the section is increased. Grain size is not specified and the manufacturer guarantees a certain level of impact strength.

In the American system (AISI) the specifications require fine grain size and

either composition within a very narrow range or hardenability as measured by the Jominy test within a narrow band. Since it was determined by Crafts and Lamont²⁶ that for fine-grained steels there is a definite relation between degree of hardening in quenching, tensile strength after tempering, and impact strength, there is no essential difference between the properties that are guaranteed by both types of specification. In fact, tables comparable to the British specifications have been proposed for comparison of alternative American steels.

In practice it has been found that the American system seems to require somewhat less alloy content on account of more closely estimated hardenability requirements. The British system, on the other hand, is more tolerant of errors in heat treatment, and the specification may give a lower incidence of incomplete hardening. Both systems seem to be satisfactory to the respective makers and users of the steels. In order to try to evaluate whether there is a useful difference in quality between coarse and fine-grained steels, the relation²⁶ between hardenability, tensile strength and impact strength that was determined for American steels was applied to two series of British steels. One series of data came out of a study of British steels²⁷ to permit interchange of specifications and the other came from the work of Swinden and Bolsover²⁸. Steels with compositions greatly different from those of the American SAE-AISI types as well as carbon steels were discarded. In the first group hardenability data were available for a direct comparison. The impact strength was calculated from the hardenability curve and the hardness of the quenched and tempered steel. The average of the calculated impact strengths was within 2 ft.-lb. of the average of the actual values in the fine-grained steels of the group. In the steels that were not fine-grained the deviations of the actual values from the calculated values are shown in Fig. 14. It is evident that the average of

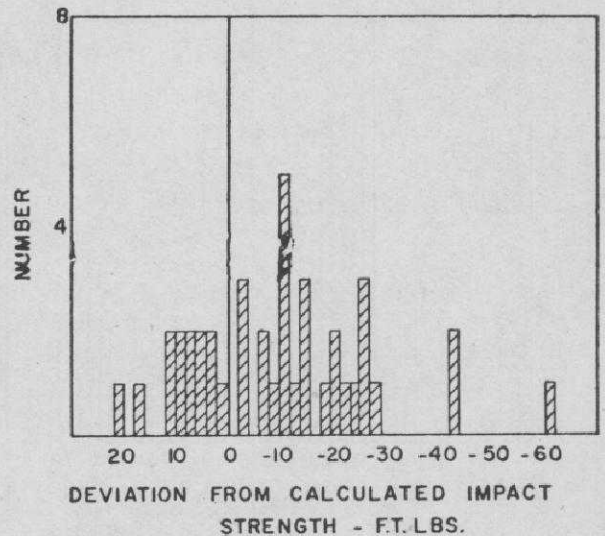


FIG. 14 — EFFECT OF GRAIN SIZE ON THE IMPACT STRENGTH OF LOW-ALLOY STEELS REPORTED BY CRAFTS AND LAMONT²⁷

the group is significantly below the impact strength expected of fine-grained steels.

A similar comparison was based on data from the classic paper of Swinden and Bolsover. It will be recalled that they split heats into fine and coarse-grained parts and tested them in a range of section sizes. They tested a wide variety of alloy steels of the type under consideration. The impact strengths of the fine-grained specimens were corrected by the Crafts and Lamont method to a hardness equivalent to the coarse-grained specimens. The comparison, shown in Fig. 15, confirmed that there is a marked tendency for the coarse-grained steel to have a relatively lower impact strength. Since this method makes no allowance for the greater hardenability of the coarse-grained steel, the true difference is even greater than is indicated. Some of the coarse-grained steels were abnormally low in impact strength, but no obvious explanation could be discerned.

The spread of data over ± 20 ft.-lb., however, is the normal error that can be expected in impact tests. Thus, even though individual impact test results are subject to a wide range of error, it is clear that fine grain size

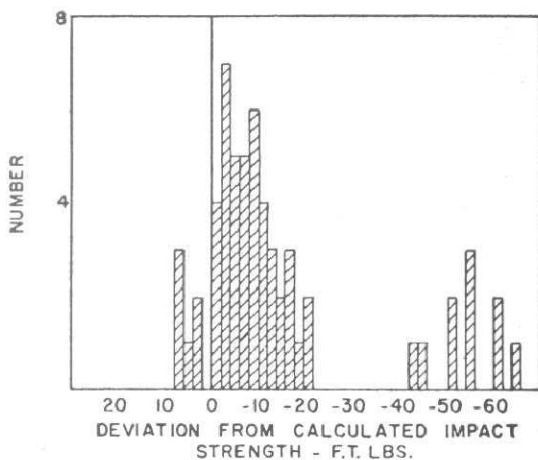


FIG. 15 — EFFECT OF GRAIN SIZE ON THE IMPACT STRENGTH OF LOW-ALLOY STEELS REPORTED BY SWINDEN AND BOLSOVER²⁸

adds about 10 ft.-lb. to the average. This is gained with a small loss of hardenability. However, since the method of specifying fine grain size and hardenability requires actually less rather than more alloy, it would appear that the additional toughness justifies the use of fine-grained steel.

Summary

In this review of factors in the deoxidation practice that affects the quality of alloy steel, it is evident that the chemistry of the deoxidizing reactions in the liquid metal represents only a part of the art of making clean steel. It has been demonstrated that, regardless of the final composition of the metal in the ingot molds, the inclusions reflect the degree of oxidation prior to the final deoxidizing treatment. For this reason, it is not only necessary that the dominant inclusion-forming elements, oxygen and sulfur, be controlled at the end of heat, but that oxygen should also be maintained at a minimum level during the finishing period by suitable slag practice and initial deoxidation.

Clean steels, with good hot-working characteristics and sound etch tests, are made in the basic arc furnace by deoxidizing the slag

to produce a reducing condition, so that oxygen is allowed to come into equilibrium with the carbon content. Effective sulfur reduction requires, in addition, the presence of a deoxidizing element in the metal.

In basic open-hearth furnaces the most effective practice is to charge a lean slag, raise the temperature rapidly, and maintain an active boil throughout the finishing period. It is helpful if the carbon boil is blocked at the highest possible carbon content with a strong, low-carbon initial deoxidizer, such as silico-manganese. Under no circumstances should a reboil be permitted to develop after blocking.

The solidification diagrams of the most commonly encountered oxide-sulphide systems have been indicated. The more simple systems are fairly well established. The more complex diagrams, however, are largely unsupported, and, since they are quite difficult to understand, they are suggestive only and should be interpreted in relation to actual experience.

Most alloy steels are given a final deoxidation with conventional amounts of manganese and silicon. Coarse-grained steels are usually treated with small amounts of aluminum, titanium, or zirconium to improve surface and working properties. Calcium is usually added to improve transverse ductility in heavy forgings and castings.

Fine grain size in low-alloy steel is usually desirable, even when it is not specified, in order to develop maximum toughness in normal steels and to avoid occurrence of excessive brittleness. Fine grain size is usually developed by the addition of an effective amount of aluminum or vanadium. The possibility of refractory, segregated aluminum oxide formation is minimized by suitable slag practices and strong initial deoxidation in the furnace. Entrapment of slag or refractory inclusions may be minimized by avoidance of cold heats, excessive turbulence, and poor quality ladle and runner bricks.

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