

Edge Cracking in Hot-Rolled Coils of Semi-killed Steels

A. Saxena, V. Kumar, P.P. Sengupta, and S.K. Chaudhuri

Various processing parameters leading to edge cracking in hot-rolled coils are described, along with a study of the effect of these parameters on the occurrence of edge cracking during commercial production of semi-killed hot-rolled coils. High-temperature tensile testing revealed that ductility decreased with a decrease in test temperature from 850 to 750 °C and improved with a further drop in temperature. This phenomenon is attributed to the closed-packed structure of single-phase austenite at higher temperatures, which transforms to ferrite + austenite at the intermediate temperature range. Edge cracking was frequently observed in hot-rolled coils that were finish rolled within this intermediate temperature range. Optical microscopy revealed large ferrite grains near edges of the coil as well as at inner surfaces of cracks caused by decarburization at higher temperatures. A minimum manganese/sulfur ratio of 12 to 8 for a sulfur level of 0.03 to 0.04%, proper teeming practice, adequate soaking, and a finish rolling temperature above 875 °C resulted in overall improvement in the edge quality of hot-rolled coils.

Keywords deoxidation, edge cracking, inclusions, Mn/S ratio, hot rolled coils, hot working, semi-killed steel

1. Introduction

Edge cracking in hot-rolled coils made from ingots has been a serious quality problem for many steel producers. The additional number of processing steps involved in the production of coils from ingots (i.e., teeming, soaking, and processing the ingots into slabs) may have a bearing on the overall quality of the coils. This paper describes the effect of processing parameters during steelmaking and hot rolling on the edge quality of coils, along with the results of a study carried out to identify these parameters.

2. Effect of Processing Parameters

Deoxidation practice strongly influences the evolution of dissolved gases, leading to the formation of blowholes during solidification in the mold. Blowholes located near the ingot surface may be exposed and oxidized during further processing, resulting in oxide formation and subsequent crack initiation. Therefore, the formation of blowholes must be either suppressed or shifted well inside the skin of the ingot.

Silicon is used as a deoxidizer in steel. Too low an amount may cause underdeoxidation, leading to the formation of subcutaneous blowholes. The presence of sulfur induces hot shortness in two ways: (1) Formation of a low-melting-point phase (FeS) at the grain boundaries decreases their shear strength, and (2) a solid solution of sulfur strengthens the austenite, thus increasing the tendency of crack formation in the grain boundaries (Ref 1). Carbon lowers the sulfur solubility in γ-iron to about 70 to 80% of the value for pure iron, thus indirectly counteracting to some extent the deleterious effect of sulfur (Ref 1). Manganese is useful for taking care of hot shortness, since it has a higher affinity than iron toward sulfur. The empirical relationship shown in Eq 1 (Ref 2) can be used to ascertain the concentration of manganese required to eliminate hot shortness in high-sulfur steel:

$$\%\,Mn = 0.3 + 1.7\%\,S \quad \text{(Eq 1)}$$

Manganese in solid solution also decreases the sulfur solubility in γ-iron. The lower amount of sulfur in solid solution will result in a lower resistance to dislocation movement within the metal matrix (Ref 1).

Oxygen has a low solubility in γ-iron and thus cannot be expected to increase the resistance to dislocation movement or to form oxide precipitates at grain boundaries. It also somewhat lowers the sulfur solubility in γ-iron. Oxygen per se does not cause hot shortness in manganese-free steels, but it counteracts to some extent the beneficial effect of manganese, when present, since it lowers the effective manganese content in the austenite by forming (Fe,Mn)O and thus promotes hot shortness. Large oxide inclusions caused by inhomogeneous absorbed oxygen are very effective in developing local hot shortness (Ref 1).

Inclusions greatly influence the deformability of a steel, since inclusion plasticity plays a significant role in the decohesion phenomenon of the inclusion/matrix interface. Malkiewitz and Rudnik (Ref 3) proposed a deformability index, ν, to study the deformation behavior of inclusions in a steel matrix at different temperatures, pressures, velocities, and so on:

$$\nu = \frac{\varepsilon_i}{\varepsilon_m} \quad \text{(Eq 2)}$$

where ε_i is the ellipsoidal deformation of a spherical inclusion and ε_m is the corresponding deformation of the surrounding steel matrix. If the deformation index is zero, the inclusion does not deform at all. For an index value of unity, the reverse phenomenon will prevail; the inclusion will deform as much as the matrix. Using this criterion, the characteristics of inclusions normally found in steel can be categorized (Ref 4):

- FeO, MnO, and (Fe,Mn)O inclusions are intrinsically deformable at ambient temperature, but not at the higher temperature range of 400 to 800 °C.

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- Al_2O_3 and calcium-aluminate inclusions are undeformable at all temperature ranges involved during hot processing.
- Double oxide inclusions of the spinel type $AO \cdot B_2O_3$ are undeformable at all temperature ranges during hot processing.
- Silicates are undeformable at ambient temperature and become highly deformable at the temperature range of 800 to 1000 °C.
- MnS is highly deformable up to a temperature of 1000 °C, and its plasticity decreases with further increase in temperature.

Table 1 Chemical analysis of the coil

Edge condition	Composition				
	C, wt%	Mn, wt%	Si, wt%	S, wt%	O, ppm
Cracked	0.12	0.58	0.01	0.033	780
Uncracked	0.11	0.55	0.01	0.035	450

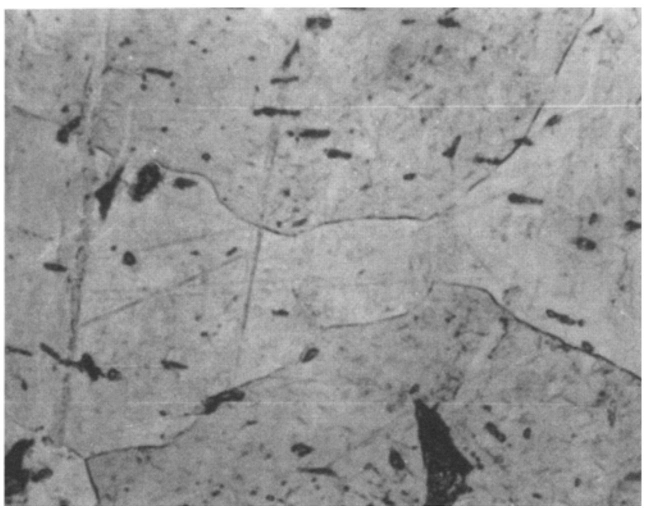


Fig. 1 Microstructure showing large grains near the cracked edge. 500×

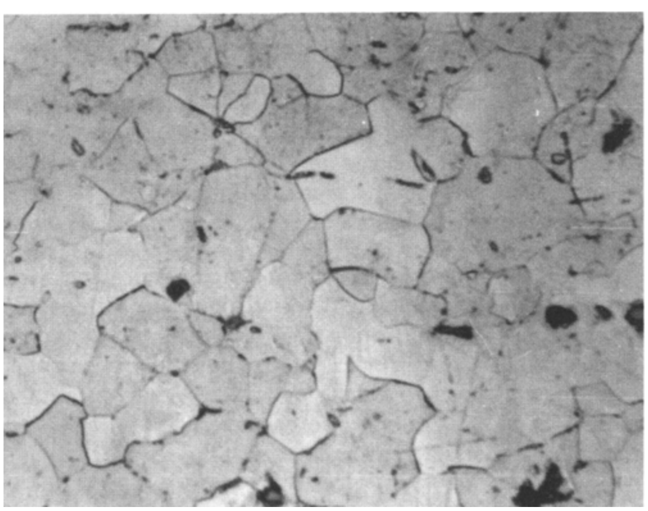


Fig. 2 Microstructure showing smaller equiaxed grains at the uncracked edge. 500×

The first three types of inclusions are undeformable at the hot processing temperature range of steel and will act as stress raisers, leading to crack initiation. Note that all these types of inclusions are simple or complex oxides. Therefore, an effort should be made to control the oxygen level in the steel.

Cracking during hot working can be compared with the creep phenomenon. However, the strain in hot working is large (0.5 to 500 s^{-1}) compared to tension or creep tests and usually is carried out at temperatures above 0.6 T_m (Ref 5). Two types of cracking may occur in hot working (Ref 6): wedge-type cracking and the formation of roughly spherical cavities at the grain boundaries. Wedge-shaped cracks (w-type cracking) initiate mostly at grain boundary triple points and propagate along grain boundaries that are roughly normal to the applied stress. The shear stress required to nucleate a w-type crack has been calculated by Smith and Barnby (Ref 7) based on grain-boundary sliding at triple points:

$$\tau = \left[\frac{3\pi\gamma_b G}{8(1-\nu)L}\right]^{1/2} \quad \text{(Eq 3)}$$

where γ_b is the grain boundary surface energy, G is the shear modulus, and L is the grain-boundary sliding distance (assumed equal to the grain diameter).

Round or elliptical cavities in the grain boundaries (r-type cracking) form at the higher temperatures under lower stresses. Grain-boundary sliding is necessary to initiate r-type cavities. The shear stress to initiate r-type cavities at grain-boundary particles or ledges of width $2c$ and spacing $2d$ was estimated by Smith and Barnby (Ref 8) as:

$$\tau = \frac{\pi}{2}\left(\frac{c}{d}\right)^{1/2}\left[\frac{4\gamma_b G}{(1-\nu)d}\right]^{1/2} \quad \text{(Eq 4)}$$

Stiegler et al. (Ref 9) have shown that all cavities are initially polyhedral, but change shape depending on whether grain-boundary sliding or vacancy diffusion predominates according to the conditions of temperature and stress.

After tapping, shorter ladle holding time will not allow inclusions to coalesce and float, thus increasing the inclusion content. Longer ladle holding time will cause a significant drop in the temperature of liquid steel, which may cause problems during teeming. Therefore, ladle holding time must be optimized for a specific grade of steel.

Selection and preparation of the mold coating play vital roles in the formation of subcutaneous blowholes in steel. A coating mixture with a high percentage of volatiles, if poorly dehydrated, can promote evolution of excessive gases when it contacts the liquid steel. At high temperature, the escaped water vapor will dissociate into nascent hydrogen and oxygen gas. The oxygen will then oxidize the iron to form iron oxides, which will combine with carbon in the liquid steel to form carbon monoxide gas. During solidification, these gases will form subcutaneous blowholes. This type of problem generally occurs when the mold coating is too thick. In such cases the volatile gases will find no time to evolve completely and will remain trapped in the form of fine bubbles below the level of the metal meniscus.

Ferrostatic pressure, which is directly related to the height of the hot metal in the ingot, affects the removal of nonmetallic inclusions and gases. Conditions for this removal deteriorate with an increase in height, because the inclusions find it difficult to float up and evolving gases are entrapped as the height of metal increases. However, rather than reducing the height of the ingot alone, it has been found that a reduced H/D ratio (where H is the height of the hot metal and D is the square root of the cross-sectional area of the ingot at half its height) helps to eliminate these defects (Ref 10).

Teeming practice is a dominant factor in the ultimate cleanliness of the steel. A lower teeming rate will expose the liquid steel to the atmosphere for a longer time, leading to greater absorption of oxygen as manifested by a high oxide content. The ladle opening must be carefully maintained so that it forms a solid stream of liquid steel, which should be directed at the center of the mold. If the liquid steel splashes during teeming, it may hit the inner mold wall and immediately chill in the form of oxide scabs. During its rise, the molten steel will contact and react with this oxidized iron. Carbon monoxide gas thus generated may lead to the formation of subcutaneous blowholes. Some of the iron oxides may mix with the liquid steel due to intense turbulence within the mold and may remain trapped locally as oxide inclusions.

A longer soaking time and/or higher soaking temperature can cause severe oxidation of the ingot surface, which may pose problems during subsequent rolling. Excessive scale formation due to severe oxidation may expose any subcutaneous blowholes and cause cracking during rolling to slabs. Low soaking time or temperature may lead to poor deformability of the ingots during rolling. This problem is further aggravated at the edges, where the rate of cooling is high, leading to formation of minor cracks at the edges of the slabs. Therefore, a proper soaking schedule is necessary for smooth rolling of ingots into slabs without crack formation.

The importance of proper edge working has been widely reported (Ref 11-13). A proper hot rolling schedule for thickness and width control is necessary to produce good quality edges in hot-rolled coils. Excessive draft in a single pass in the initial stages of rolling may lead to unrestricted spread in the lateral direction. This can cause rupture at the edges due to the combined effect of tensile forces operating at the edges. However, reduction across the width of the slab at proper stages will check the unrestricted lateral spread and force the blowholes to weld together.

The plasticity of steel decreases significantly with decreases in hot working temperature. Therefore, a higher finish rolling temperature should be maintained to ensure adequate plasticity, particularly at the edges in order to sustain plastic deformation without risk of edge cracking. However, too high a temperature may lead to cobbling of coils. The finishing temperature must be optimized to produce good quality coils.

3. Experimental Techniques

Two-hot rolled coils of semi-killed steel were obtained with deep cracks on one edge, the other edge free of cracks. Samples were collected from both edges for detailed metallurgical investigations. The nature of the inclusions was studied on unetched samples using an optical microscope (Reichert) at a magnification of 500×, and on polished samples etched with freshly prepared 2% nital solution. Polished specimens also were used for both qualitative and quantitative electron probe microanalysis (JEOL JCXA 733). High-temperature tensile testing, using an MTS dynamic testing machine, was performed at a strain rate of 10^{-3}/s in the temperature range of 700

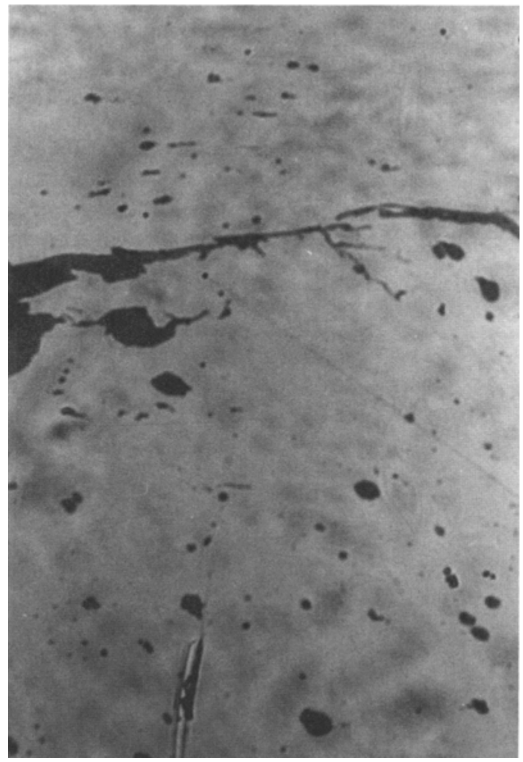


Fig. 3 Microphotograph showing a large number of inclusions near the cracked edge. 500×

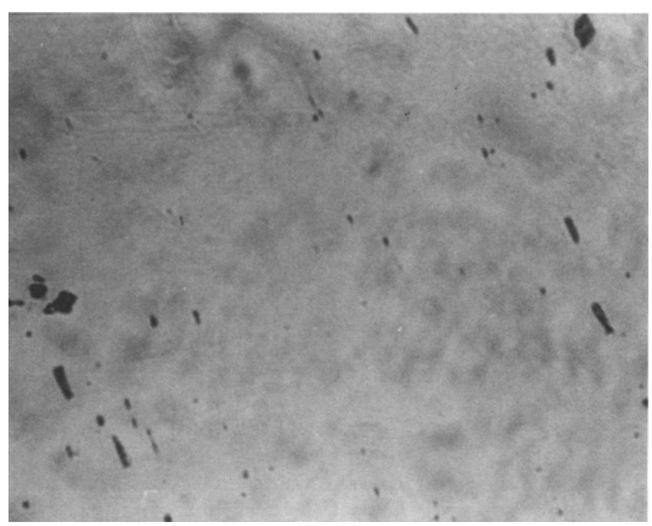


Fig. 4 Microphotograph showing fewer inclusions at the uncracked edge. 500×

to 950 °C at 50 °C intervals. Optical emission spectroscopy provided chemical analysis of carbon, manganese, and silicon, and oxygen measurement was done with the help of a LECO analyzer.

4. Results and Discussion

Examination of a large number of hot-rolled coils revealed that the edge cracking phenomenon was random with respect to location, depth, and affected length. In many coils, the cracks were confined to one side.

The specified chemistry of the steel from which samples were collected was 0.12% max C, 0.5% max Mn, 0.08% max Si, 0.05% max S, and 0.05% max P. Chemical analysis of samples from the two ends, both cracked and uncracked, revealed no significant difference in concentration levels of carbon, manganese, and silicon. However, the level of oxygen at the cracked edge was found to be nearly twice as high as that at the uncracked edge (Table 1). This may be attributed to the larger number of oxide inclusions observed at the cracked edges.

Typical microstructures in the transverse through-thickness direction of the cracked and uncracked edges of the coil revealed the presence of coarse ferrite grains in the vicinity of cracks (Fig. 1). However, the ferrite grains away from cracks as well as in the uncracked edge were finer and equiaxed (Fig. 2). This may be due to decarburization at the coil edges as well as at the inner surface of the cracks at high temperature.

The role of inclusions during crack initiation and propagation was studied by optical microscopy. The inclusion content near the cracks was usually higher compared to that at the uncracked edge (Fig. 3 and 4). Some inclusions were also found to be associated with cracks running from the edge to the center of the coil. Thus, crack propagation in the through-thickness direction was facilitated by the presence of such inclusions.

Electron probe microanalysis showed small, irregularly shaped inclusions to be oxides of aluminum and silicon (Fig. 5), and large, spherical inclusions to be oxides of iron and manganese (Fig. 6). The spherical oxides were randomly placed

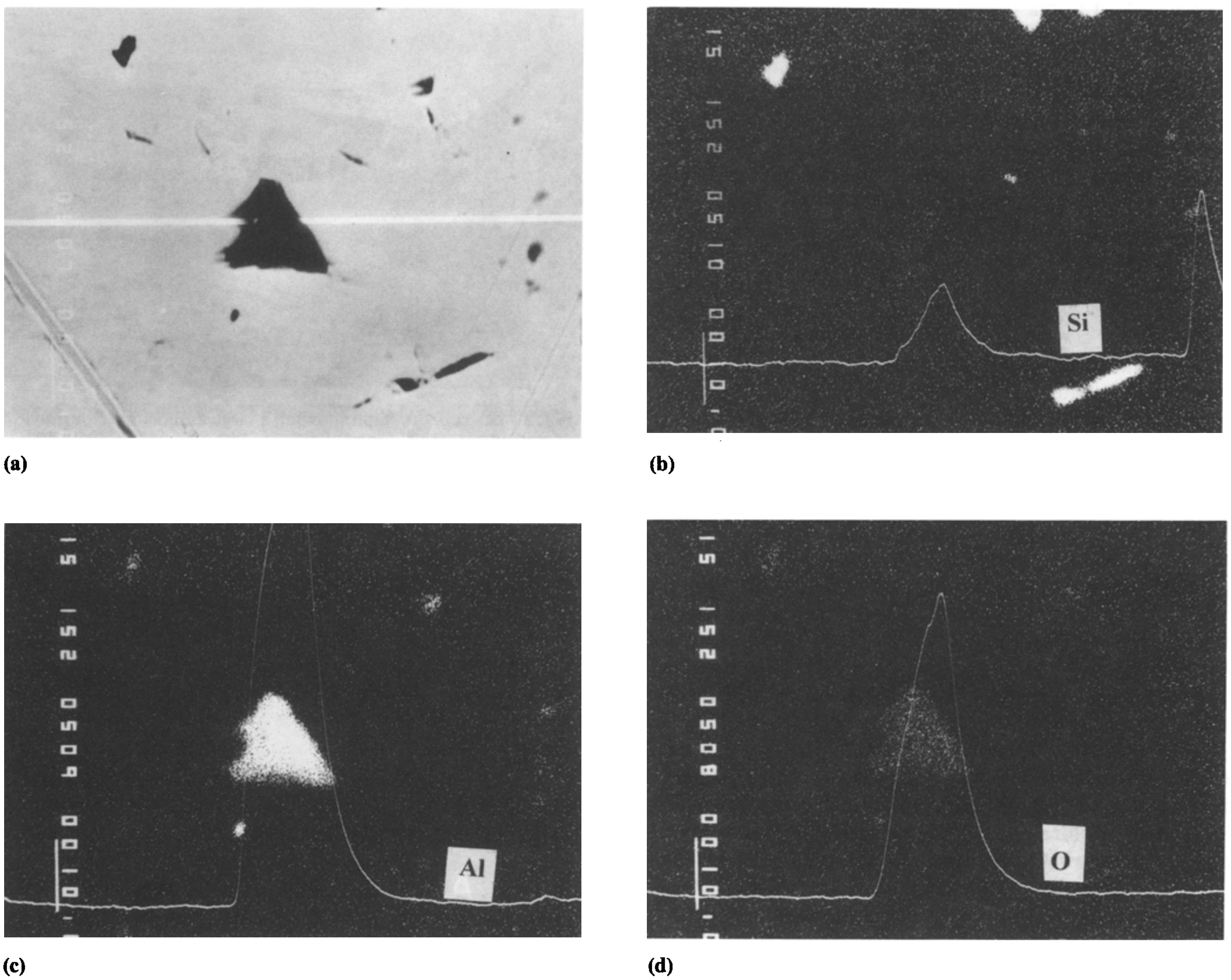


Fig. 5 Electron probe microanalysis of an irregularly shaped particle. (a) Backscattered electron image. (b) Silicon. (c) Aluminum. (d) Oxygen

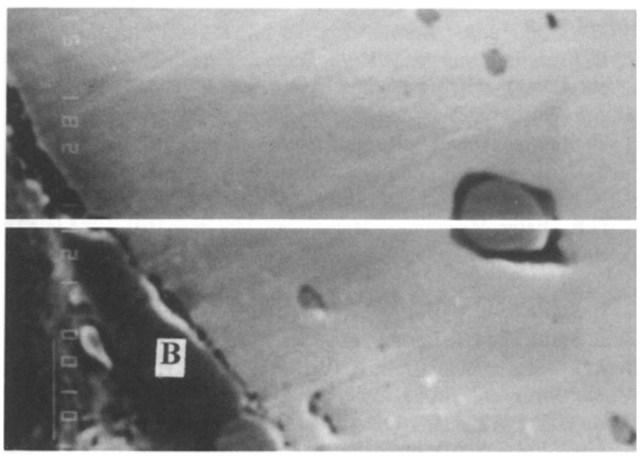
and were quantitatively analyzed to study the possible role of burning on edge cracking. This was done at oxides in the vicinity of the decarburized layer as well as at oxide particles located inside. The results obtained are summarized in Table 2, which shows that the oxides along the decarburized layer were pure iron oxide, whereas the oxides inside were complex oxides of iron and manganese. This rules out any possibility of localized burning of coils during high-temperature soaking of the ingots or slabs.

To examine the hot ductility of the steel, high-temperature tensile testing was carried out at 700 to 950 °C, the range in which finish rolling generally is carried out. The elongation values obtained are plotted against temperature in Fig. 7, which shows that ductility decreased sharply when temperature decreased from 850 to 750 °C and increased with a further drop in temperature to 700 °C. This type of ductility minimum behavior has also been reported by Rhines and Wray (Ref 14).

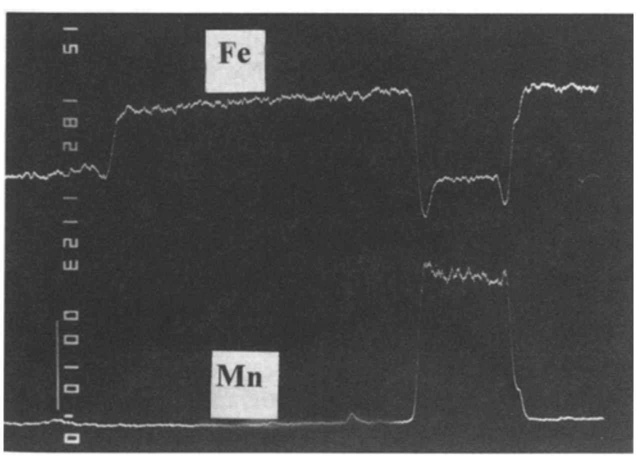
This phenomenon is attributed to the transformation behavior of the steel. The steel is austenitic above Ac_3 (approximately 875 °C). Austenite transforms to ferrite as the temperature is lowered below Ac_3. Since the stacking-fault energy of austenite is much lower compared to the stacking-fault energy of ferrite, ductility drops significantly with an increase in the volume fraction of ferrite and a simultaneous decrease in the volume fraction of austenite. At Ac_1, remaining austenite transforms to pearlite; the volume fraction of pearlite depends on the carbon content in the steel (approximately 8 to 10% in the present steel). The presence of pearlite decreases the sliding distance, $2d$ in Eq 5; therefore, the required stress is high, leading to higher ductility. Ductility remained almost unchanged from 850 to 950 °C due to the presence of a single-phase austenite at this temperature range.

Based on these experimental observations and theoretical considerations given elsewhere, the processing parameters that may lead to edge cracking of hot-rolled coils of semi-killed steel were identified as (1) manganese/sulfur ratio, (2) teeming practice, and (3) finishing temperature.

The manganese/sulfur ratio is important because manganese takes care of sulfur present in the steel and prevents hot shortness. However, if present in excess (Eq 1), it may oxidize



(a)



(b)

Fig. 6 Electron probe microanalysis of a spherical particle. (a) Backscattered electron image. (b) Iron and manganese

Table 2 Quantitative analysis of oxides at the cracked surface and away from the cracked edge

Element	Location A	Location B
Carbon	0.000	0.000
Silicon	0.007	0.000
Aluminum	0.025	0.003
Magnesium	0.000	0.000
Chromium	0.197	0.000
Copper	0.000	0.000
Iron	47.079	67.463
Manganese	27.589	0.087

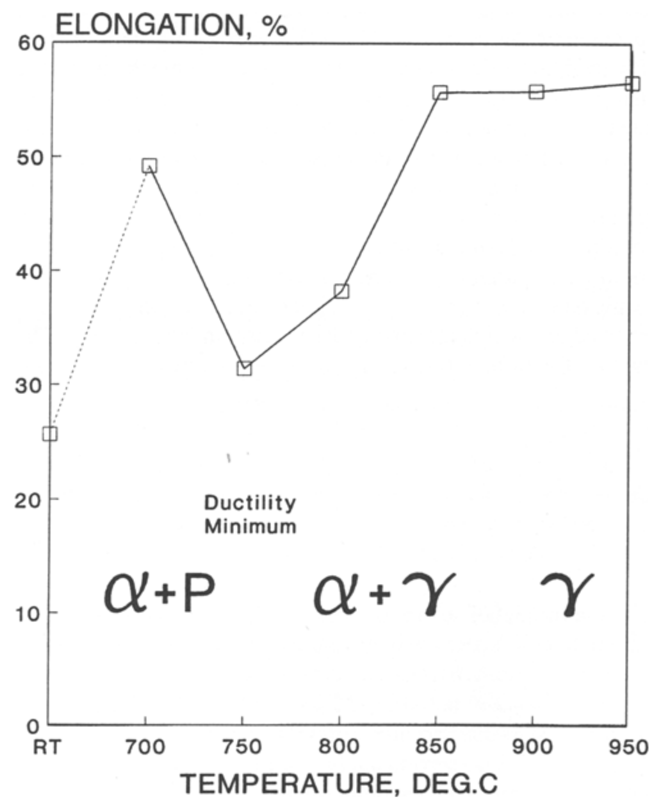


Fig. 7 Effect of temperature on steel ductility

Table 3 Summary of observations made during commercial production of hot-rolled coils following specified processing parameters

Parameter	Range
Carbon, wt%	0.08-0.10
Silicon, wt%	0.05-0.08
Manganese, wt%	0.40-0.50
Sulfur, wt%	0.03-0.05
Manganese/sulfur	9-13
Soaking temperature, °C	1300-1320
Finish rolling temperature, °C	850-890

and form oxide inclusions that help in the nucleation and/or propagation of cracks. Therefore, the manganese/sulfur ratio must be maintained in an optimum range where hot shortness is prevented but oxide inclusions do not form. According to Eq 1, a manganese/sulfur ratio in the range of 8 to 12 is adequate to take care of hot shortness for the sulfur level generally present in the steel under study.

As stated earlier, teeming practice strongly influences the ultimate quality of the steel. Edge cracking of coils on one side only can be explained by the fact that teeming sometimes occurs off-center, resulting in splashing of metal toward one side of the mold wall and leading to entrapment of blowholes as well as formation of oxide inclusions on one side of the ingot. This explains the presence of excess oxygen at the cracked edge.

The finish rolling temperature was in the range of 850 to 880 °C. Since the Ac_3 temperature is 875 °C for the steel under investigation, rolling was carried out in the two-phase region: ferrite + austenite. At higher temperature, the predominant softening mechanism is dynamic recrystallization since the austenite at this temperature has a low stacking-fault energy. However, at lower temperature, the softening mechanism may change from dynamic recrystallization to dynamic recovery due to the presence of ferrite with a high stacking-fault energy. The grain-boundary area decreases with increasing grain size (possible during dynamic recovery). This may lead to intergranular cracking due to grain-boundary sliding. Since the temperature at the edge decreases rapidly due to the higher rate of cooling compared to the center of the coil, softening due to dynamic recovery is predominant. Therefore, cracking may occur at the edges, which are also under maximum tensile stress. The volume fraction of ferrite increases with decreasing temperature. Thus, the finish rolling temperature should be kept close to Ac_3.

A number of heats were monitored with respect to the processing parameters that influence coil edge quality. The observations thus made are summarized in Table 3. When these parameters were controlled within the specified limit, the edge quality of the coils was good.

5. Conclusions

Based on the experimental findings, the following conclusions can be drawn:

- A manganese/sulfur ratio in the range of 8 to 12 produced good quality coils.
- Both simple as well as complex oxide inclusions were detrimental.
- Teeming practice played a significant role in the formation of subcutaneous blowholes. Therefore, a well-centered solid stream of hot metal should be maintained.
- Finish rolling should be carried out in the single-phase region—that is, at a temperature above 875 °C.

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