Investigation of Panel Crack Formation in Steel Ingots: Part II. Off-Corner Panel Cracks

B. G. THOMAS, I. V. SAMARASEKERA, and J. K. BRIMACOMBE

Model predictions of the thermal and stress evolution in steel ingots, combined with a metallurgical study, have confirmed the mechanism of formation of off-corner panel cracks. The cracks are generated initially in the subsurface of the ingot during the early stages of reheating in the soaking pit. The volume change associated with γ-α transformation plays a major role in the generation of the tensile stresses as in the case of the mid-face panel cracks. Early in the reheating, a subsurface two-phase zone of α and γ contracts within a surrounding field of austenite and is placed in tension. Crack formation is enhanced by the precipitation of AlN which embrittles the steel. The subsurface cracks subsequently may penetrate to the surface of the ingot immediately upon its withdrawal from the soaking pit owing to the generation of surface tensile stresses caused by rapid cooling of the ingot surface. Measures to minimize formation of off-corner panel cracks, therefore, include reducing air cooling time (prior to charging ingots to the soaking pit) to prevent γ-α transformation, reheating the ingots slowly in an initially cold soaking pit to reduce the tensile stresses, increasing the air cooling time substantially to force the cracks farther from the surface, and minimizing soaking times and temperatures.

I. INTRODUCTION

OFF-corner panel cracks run in a discontinuous manner along the edges of the wide faces of large, low-carbon, steel ingots. These cracks often form rough oval patterns on the wide face of the ingot and sometimes also on the transverse section as seen in Figure 2 of Part I[1] and in Figure 1. While the exact time of crack formation is unknown, it is associated with reheating since off-corner panel cracks are discovered only after removal from the soaking pit. The cracks also are affected greatly by the extent of cooling prior to reheating. Ingots that experience more than two hours of air cooling, or are allowed to grow completely cold prior to reheating, seldom experience problems.[2,3] Like mid-face panel cracks, the defect is believed to arise through a complex combination of reduced elevated-temperature ductility and stress generation. In Part II of this paper, the results of a metallurgical study of off-corner panel cracks and model predictions of thermal and stress evolution in affected ingots are presented. From these, a detailed mechanism for the formation of the cracks is formulated and solutions to the problem are proposed.

Fig. 1 — Location of off-corner panel cracks found by Sussman et al. in transverse cross-section near the top of a large, corrugated ingot subjected to 108 min air cooling.[4]

II. METALLURGICAL INVESTIGATION

To develop a more complete understanding of how off-corner panel cracks are manifested, a metallurgical investigation was conducted prior to mathematical modeling. Since the cracks are easily discernible only after rolling has started, obtaining a sample from an unrolled ingot containing off-corner panel cracks is exceedingly rare. Nonetheless, such an ingot was found (Figure 2 in Part I),[3] the cross-section
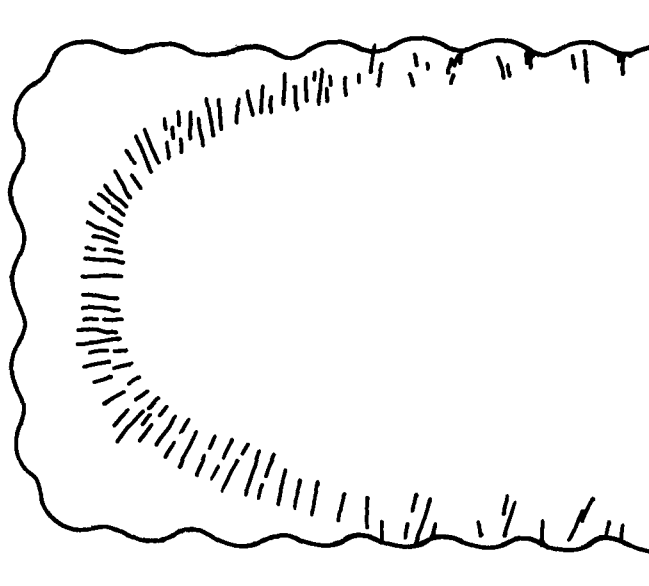
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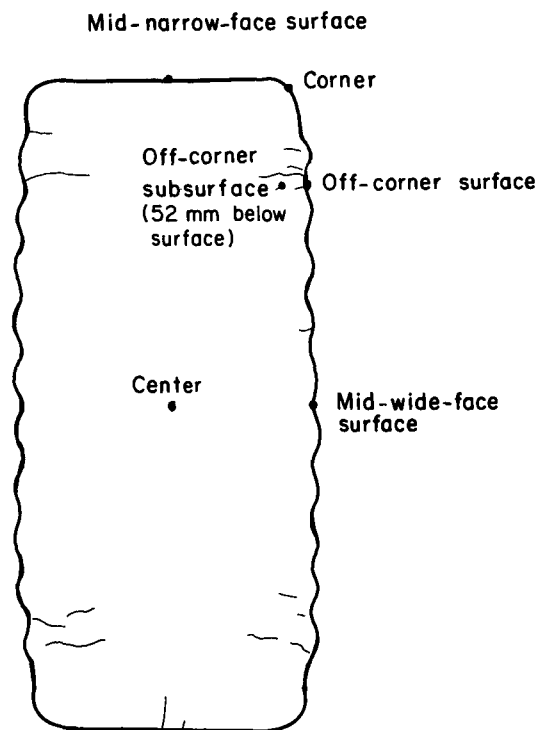Manuscript submitted August 19, 1987.

of which is traced in Figure 2 (which also illustrates the terminology used for specific locations). The internal crack pattern differs somewhat from that found by Sussman et al.,[4] Figure 1. Samples containing cracks were taken from the lower left-hand corner region at approximately mid-height of the ingot shown in Figure 2. The composition of this ingot was typical of crack-prone steels and contained 0.14 pct C, 1.40 pct Mn, 0.008 pct P, 0.005 pct S, 0.28 pct Si, 0.054 pct V, 0.039 pct Nb, 0.031 pct ASA, 0.28 pct Ca, 0.358 pct Ni, 0.033 pct Cr, and 0.002 pct Mo.

An HCl macroetch of a sectioned sample containing a complete off-corner panel crack is presented in Figure 3. The association of the cracks with mold corrugations can be seen as the crack intersects the surface of the ingot close to the "off-corner location", or the valley between the first

Mid-narrow-face surface

Fig. 2 — Location of off-corner panel cracks in a transverse section through a 760 × 1520 mm ingot.[3]

two corrugations. Beneath the surface, it bends and lies directly below the first corrugation peak and extends to a maximum depth of about 180 mm. In the plane of the sample, the crack appears discontinuous, but a closer examination revealed that the major internal cracks link into a continuous, complex network to the ingot surface. The crack surfaces are oxidized and the cracks are bordered by a zone of decarburization containing fine precipitates.

Figure 3 also reveals the presence of an extensive network of long, thin lines that appear to represent the prior austenite grain boundaries of very large, elongated, columnar grains. This network can be distinguished more easily in Figure 4 which was traced from the original structure. The apparent ASTM grain size of 2 is very large with single grains having dimensions of 5 × 40 mm. The long, thin shape of the boundaries that extend perpendicular to the surface in the direction of heat flow is characteristic of the original columnar grain structure. The association of the intergranular cracks with this network corroborates the literature findings that the cracks follow the prior austenite grain boundaries.[2] This indicates severe grain boundary weakening at some time during ingot processing.

A micrograph of the decarburized ferrite band associated with the major panel cracks is shown in Figure 5(a). The band contains precipitates that were identified under a scanning electron microscope to consist of (Fe, Mn) silicates, (Fe, Mn) sulfides, and Fe oxide. These are presumably products of internal oxidation. Although no AlN precipitates were found, they were not expected, owing to their small size and the oxidized condition of the fracture surface. Elsewhere in the ingot, apparently sealed cracks were observed with only the decarburized band, containing precipitates, remaining (Figure 5(b)).

The intersection of two different ferrite bands is shown in Figure 6. The first is a major decarburized panel crack similar to the one in Figure 5 while the second is simply a

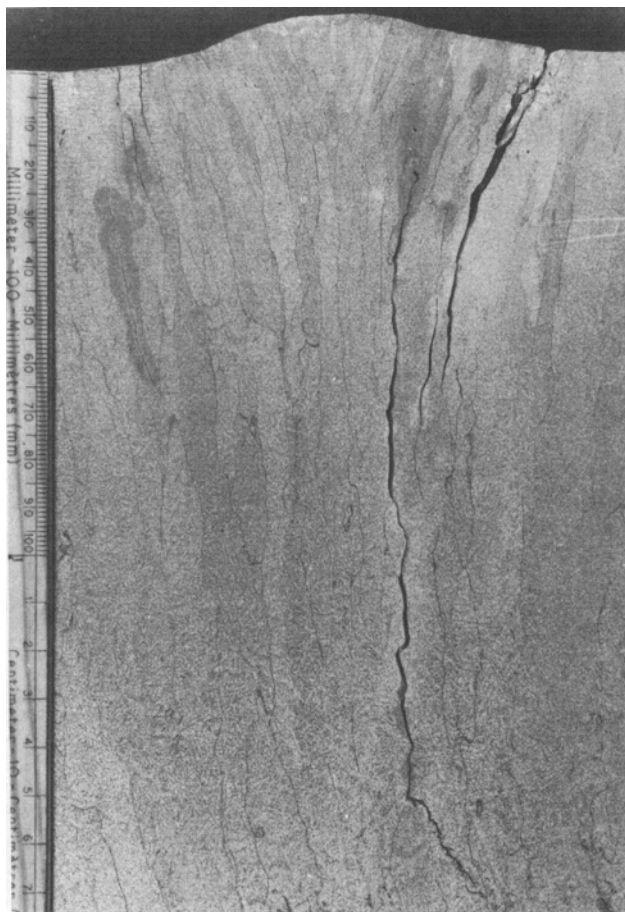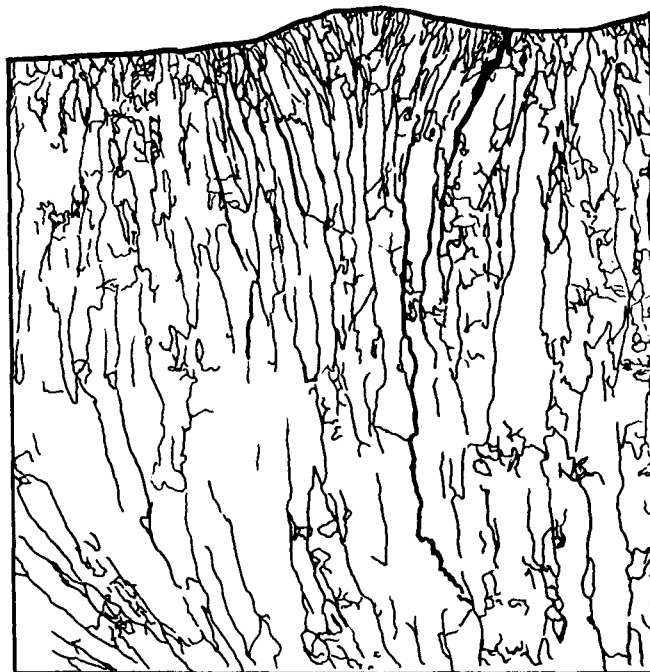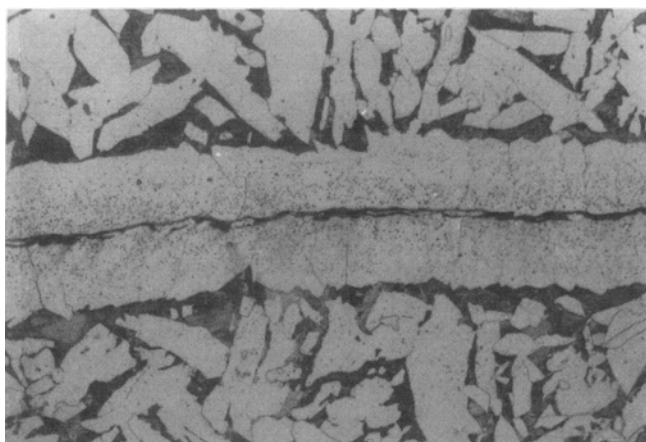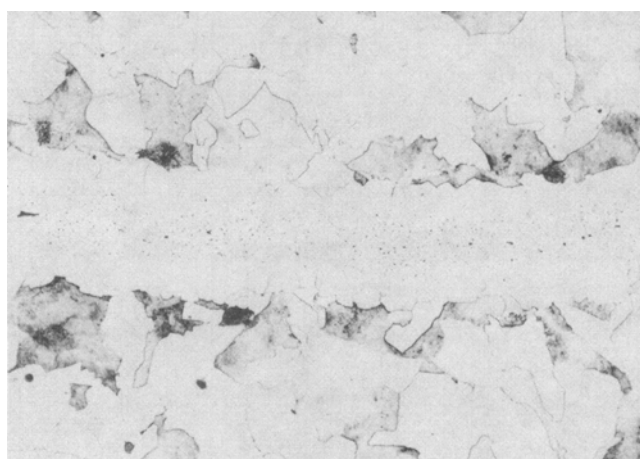Fig. 3 — Complete example of off-corner panel crack in sectioned sample taken from ingot in Fig. 2 (macroetched in HCl).

Fig. 4 — Network of ferrite bands and cracks at prior austenite grain boundaries traced from macroetched sample in Fig. 3.

(a)

(b)

Fig. 5—Decarburized ferrite band containing precipitates (etched in 2 pct nital): (a) including panel crack, (b) with no crack. Magnification of (a) 60 times, of (b) 90 times.

band of ferrite containing neither precipitates nor cracks. This band presumably contains pro-eutectoid ferrite and arises during the initial stages of $\gamma \rightarrow \alpha$ phase transformation due to preferential nucleation at the austenite grain boundaries. It is interesting to note that this type of ferrite band was also found frequently in noncracked ingots.[5] The surrounding Widmanstätten structure is indicative of higher cooling rates, consistent with the proximity of this sample to the ingot surface.

Figure 7 shows a thin panel crack traversing the final ferrite-pearlite structure along an apparent band of pro-eutectoid ferrite. This is representative of a different type of fine cracks, some of which continue from the roots of the major cracks. Their lack of decarburization implies they were either isolated from the ingot surface or formed at lower temperatures. Others appear to traverse individual ferrite and pearlite grains, clearly indicating that they formed below the Ar_1 temperature. These cracks would, therefore, not be expected in ingots that are hot rolled. Figure 7 also shows diffuse bands of ferrite that do not contain cracks. These were also observed in uncracked ingots.

Evidence that the weakness associated with the prior austenite grain boundaries persists even after cooling is complete was obtained by reheating a cracked sample to 950 °C and quenching it in water. This resulted in extensive propagation of the previously existing cracks throughout the columnar grain boundary network. This experiment reinforces the industrial observation that off-corner panel cracks cannot be removed by torch scarfing which only propagates the cracks deeper into the ingot.[3]

The average grain size of the final ferrite and pearlite structure is about 0.1 mm diameter or ASTM No. 5. In the extensive oxidized region surrounding the intersection of the largest panel crack with the ingot surface, considerably larger ferrite grains are present, exceeding 0.5 mm diameter. A close-up view of this region of the ingot is given in Figure 8.

Figure 8 also shows the fracture surface of this major off-corner panel crack. At low magnification, the fracture surface appears smooth and clearly shows the rounded facets

Fig. 6—Intersection between decarburized panel crack and uncracked ferrite band. Magnification 35 times.
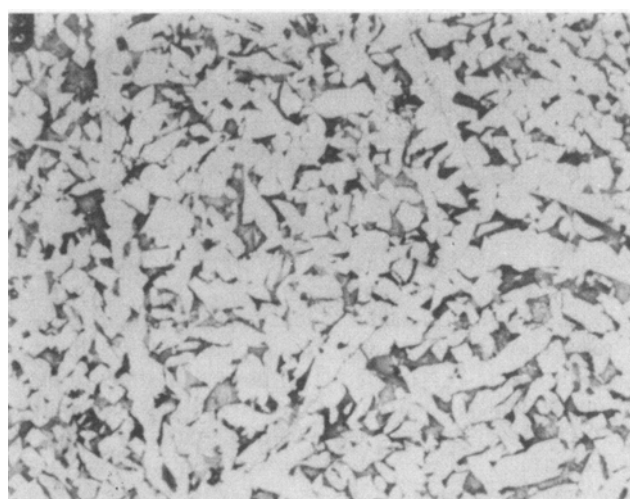

Fig. 7—Thin panel crack traversing ferrite grains in the absence of a clearly defined ferrite zone. Magnification 35 times.
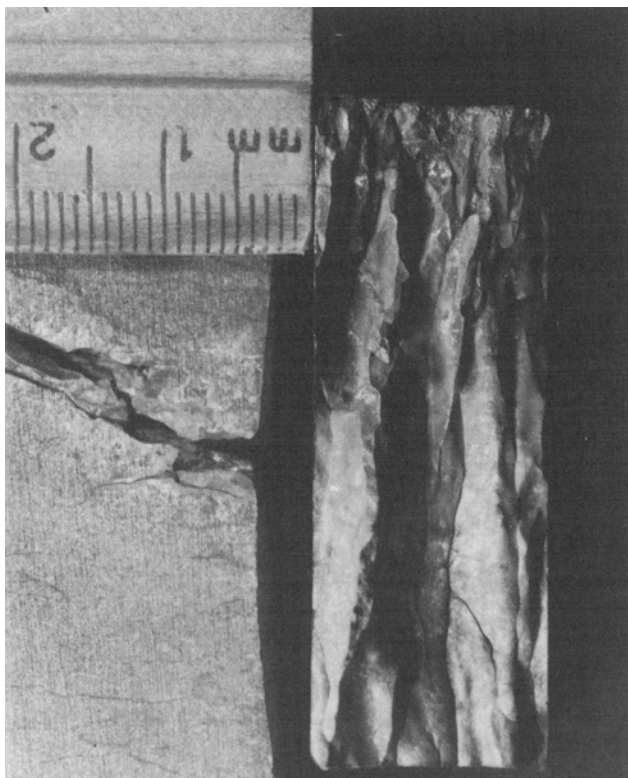
Fig. 8—Section of panel-crack tip at ingot surface; and corresponding fracture surface showing curved facets of prior austenite, columnar grain boundaries.

Fig. 9—SEM micrographs of fracture surface of off-corner panel crack.

of the prior-austenite, columnar grain boundaries. The grains become larger as they grow away from the ingot surface, as can be seen in the upper right-hand corner of the photograph.

At higher magnification, it is clear from the sequence of micrographs in Figure 9 that the apparently smooth surface is, in fact, covered with pits or fine dimples on a microscopic level. Two possible explanations can be proposed. The structure is very similar to that produced when voids coalesce around precipitates such as AlN at the austenite grain boundaries. Thus, the fracture surface may indicate a classic intergranular, ductile failure on a microscale such as was found by Suzuki[6] for low strain-rate failure between 600 °C and 900 °C. Alternatively, the structure may simply be the product of high-temperature oxidation during reheating. Indeed, an examination of the external ingot surface revealed a pitted, "swiss-cheese-like" structure that was also very similar to the fracture surface with the only major difference being that the pits were coarser and easily visible at only 5× magnification.

A sulfur print was taken to locate sulfur-rich areas in the ingot section but none was found. This reflects the very low sulfur levels (<0.005 pct S) present in this sample.

Subsequently, microprobe and SIMS surface analyses were employed to trace composition gradients across the crack surface. These analyses proved conclusively that no Mn or Si segregation was associated with the ferrite bands. Unfortunately, the low levels of the other elements present were very close to the detection limits of the probe. Thus, although no segregation of S, P, C, Nb, or Cr was found, it could not be ruled out conclusively.
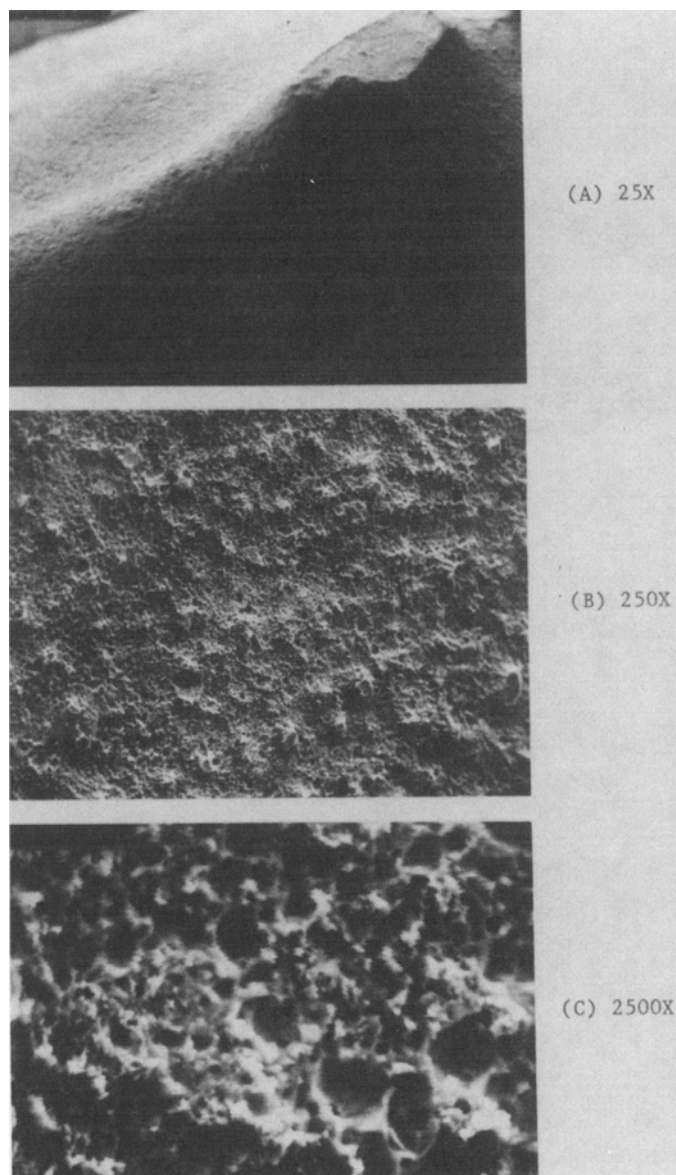
These findings confirm and augment the conclusions of previous studies:[3]

1. Off-corner panel cracks follow the smooth facets of large, weakened, columnar, prior-austenite grain boundaries.
2. The major cracks are accompanied by a thin ferrite band caused by decarburization that contains fine precipitates from the oxidation of minor alloying elements.
3. A second type of small, thin cracks traverse bands of pro-eutectoid ferrite grains and likely form during final air cooling after transformation from austenite is complete.
4. No abnormal segregation associated with the cracks or the ferrite bands could be found.
5. The region near the ingot surface of the largest crack is heavily oxidized and contains large ferrite grains.
6. Bands of pro-eutectoid ferrite not associated with panel cracks are found in both cracked and uncracked ingots of this composition.

III. FERRITE BAND WIDTH

Assuming that the ferrite band associated with the panel cracks is due to oxidation and decarburization, its width can be related to the time spent at elevated temperature by the empirical relation of Huber et al.[7]

$$l(\text{mm}) = 10\left[\frac{(1575 - 898 \text{ pct C})t \exp\left(\dfrac{-32,084}{T + 273}\right)}{8.5 + 6.6(\text{pct Mn} + 3.91 \text{ pct Si})}\right]^{1/2}$$

[1]

where l is the depth of the internally oxidized zone from the crack and T and t refer to the soaking temperature (°C) and time (seconds), respectively. According to Huber et al.,[7] oxygen slowly diffuses from the crack interface into the steel to react preferentially with Si, Mn, and Fe in that order. This explains the presence of the oxide and silicate precipitates found in the decarburized ferrite bands.

The most extensive decarburized ferrite band was found near the ingot surface associated with the largest, deepest panel crack shown in Figure 3. It extends to a maximum measured distance of 2 mm from the crack and has a very diffuse boundary. This severe oxidation is due to its proximity to the surface scale layer so that use of Eq. [1] is invalid at this location: times in excess of 75 hours were calculated, even at 1350 °C.

The thickness of the decarburized zone measured from other cracks near the ingot surface, such as that shown in Figure 5, never averages more than 0.15 mm. Deeper than 20 mm into the ingot, measurements at several locations along the panel cracks revealed that the ferrite zone generally has a constant width of about 0.07 mm. A crack with a decarburized zone of this thickness is shown in Figure 6. From Eq. [1], the times required to produce a zone of this thickness were calculated at different temperatures for the composition of the cracked sample. The results are 5 minutes at 1350 °C, 10 minutes at 1300 °C, 40 minutes at 1200 °C, and three hours at 1100 °C. Although the exact soaking temperature reached by the ingot is unknown, it appears that the oxidized zone is too thin for the majority of the cracks to have been exposed to the soaking pit environment for any appreciable length of time. Indeed, a zone of 0.07 mm thickness might even form during air cooling after removal from the soaking pit.

These findings suggest that, at most, only the first few centimeters of the largest cracks could have been open to the surface during reheating in the soaking pit. The remaining majority of the cracks either propagate through to the surface during the latter stages of reheating or form completely during air cooling after the ingot exits the soaking pit. The existence of some cracks with no decarburization implies that they must have formed during the latter stages of air cooling in a similar manner to mid-face panel cracks.

IV. MATHEMATICAL MODEL PREDICTIONS AND DISCUSSION

The development of off-corner panel cracks is a much more complicated process than mid-face panel cracking. To study this problem, the heat-flow and stress models were run to simulate thermal processing of a 760 × 1520 mm, corrugated, 23,000 kg low-carbon steel ingot with the input data from Table I. For the calculations, a mesh of 672 nodes and 1158 elements was established for the ingot and mold as described earlier.[8,9]

The first model simulation was designed to follow a typical ingot, such as the one analyzed metallurgically in the previous section, completely through all states of processing prior to rolling under conditions likely to produce off-corner panel cracks. The complete temperature and stress predictions have been presented as a sequence of plots over the entire ingot section in a previous two-part paper.[8,9] The features for mold and air cooling are, in general, qualitatively similar to those of the smaller ingot, but they develop over an extended time scale.

Also like the small ingot, the development of major regions of tensile and compressive stress within the ingot during processing is directly linked to the expansions and contractions that accompany the progress of the two phase $\gamma \rightarrow \alpha$ transformation zone through the ingot. However, the process of reheating has a profound influence on stress development and the accompanying formation of off-corner panel cracks, that was not previously encountered.

Regardless of whether cracks initiate internally and propagate outward, or if they start close to the surface and grow inward, they cause problems only if they penetrate the surface. Completely internal cracks usually close during rolling without leaving a trace if they were not exposed to atmospheric oxidation. Thus, in summarizing and analyzing the results, attention will be focused on the "off-corner" surface at the first corrugation trough from the corner where the cracks are ultimately observed (see Figure 2).

Figure 10 illustrates the sequence of alternating tension and compression experienced at this location in an ingot processed under the conditions given in Table I with 4 hours of cooling in the mold and 1.75 hours of air cooling prior to charging into a soaking pit to reheat for 13.7 hours. This figure presents the normal stress across the grain boundaries as a function of time in addition to the corresponding temperature history of this location so that the development of the phase transformations can be readily visualized. The

Table I. Input Data for Model Simulation of Off-Corner Panel Cracks

Ingot size	760 × 1520 mm
Steel composition	low carbon steel
	0.15 pct C, 1.50 pct Mn,
	0.35 pct Si, 0.01 pct S,
	0.01 pct P, 0.04 pct Al
Ar_1	650 °C
Ae_1	717 °C
Ac_1	725 °C
Ar_3	780 °C
Ae_3	825 °C
Ac_3	840 °C
Solidus temperature	1486 °C
Liquidus temperature	1513 °C
Initial steel temperature	1530 °C
Initial mold temperature	25 °C
Strip time (mold cooling time)	14400 s (4 h)
Initial time step size	0.9375 s
Maximum time step size	30 s

most significant feature of this graph is the presence of six distinct periods of tension during the entire processing history of this location. To formulate a mechanism for off-corner panel crack formation, these tensile peaks must be examined in the light of knowledge of metallurgical embrittlement of steel at elevated temperature. For the same reasons discussed for mid-face panel cracks in Part I, the stresses arising during cooling in the mold are unimportant to the ultimate formation of off-corner panel cracks. The additional phase transformation from delta-ferrite to austenite experienced by low-carbon steels during mold cooling has virtually no effect on stress generation, owing to the rapid plastic-creep relaxation occurring at these high temperatures.

The surface remains in compression throughout the four hours of cooling in the mold (Figure 10). Immediately upon stripping, however, the contraction accompanying the rapid cooling of the ingot surface produces a sharp tensile peak. Interestingly, the highest tensile stresses are located just below the off-corner and mid-narrow face locations, where panel cracks are ultimately observed. In addition, the principal stresses are oriented directly across the grain boundaries and the temperature is close to the Ar_3, in the intermediate-temperature ductility trough of the steel.[5] However, as this tensile zone moves inward, beneath the surface, it rapidly diminishes and changes its orientation to align parallel to the grain boundaries, thus rendering it less harmful. This tensile peak therefore has the potential to initiate only shallow surface cracks. Further evidence that deep cracks do not form prior to reheating is (1) this zone of tension does not correspond closely to the ultimate location of off-corner panel cracks, (2) there is a lack of a thick oxidized zone in the off-corner panel cracks analyzed in the metallurgical investigation, and (3) these stresses are always ex-

perienced on stripping regardless of the subsequent thermal treatment, which is known to be important. These facts imply that this initial tensile peak cannot be the controlling stress factor for off-corner panel-crack formation.

The first tensile zone then moves deeper into the ingot. It is replaced by compression at the surface while the transformation to ferrite takes place at the austenite grain boundaries during cooling from the Ar_3 to the Ar_1 temperature. A second tensile peak then follows the zone of high compression into the ingot during air cooling as the surface cools below the Ar_1 temperature. This peak is analogous to that held responsible for mid-face panel cracking and could conceivably cause off-corner panel cracks by the same mechanism, particularly after very long air cooling times when this tensile peak reaches a maximum. The only difference from the tensile stresses generated in the small 355 × 355 mm ingot by air cooling is the location of the maximum tensile stress, which reaches the off-corner location first. However, because these 760 × 1520 mm ingots are so large, the absolute stresses involved are much lower in magnitude than those encountered in the smaller ingots. In addition, off-corner panel cracks are known to be related more to reheating since ingots cooled completely to ambient temperature generally experience no problems. This tensile peak is therefore not likely to be the determining cause of off-corner panel cracks, although it might aggravate shallow cracks at the surface. Any shallow cracks that were initiated by either of these two tensile peaks during air cooling would be exposed to the soaking pit environment throughout reheating. This would explain the presence of heavily oxidized portions of off-corner panel cracks near the surface at the off-corner location that were observed in the metallurgical investigation.
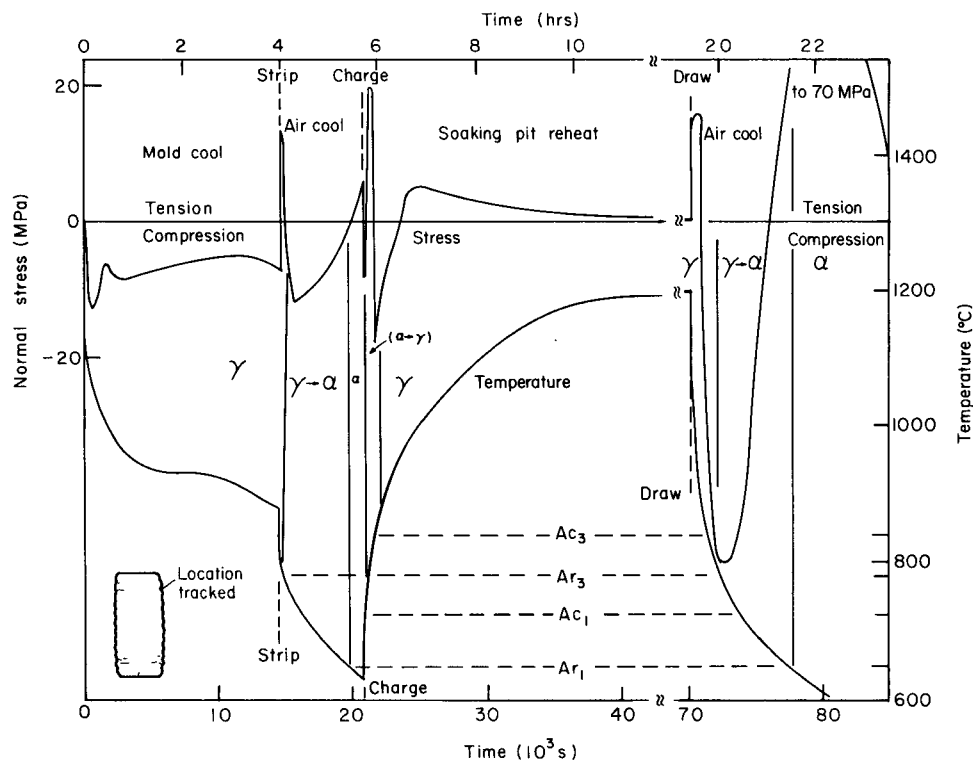

Fig. 10—Thermal and stress histories of off-corner surface location during processing of 760 × 1520 mm low-carbon steel ingot.

Shortly after charging to the soaking pit, a third tensile peak is experienced. It starts at the surface of the wide face almost immediately upon charging. At this time, cracks are unlikely to initiate at the surface. This is because the exterior of the ingot has experienced a brief time interval below the Ar_1 temperature, which would greatly improve its ductility. As discussed in a previous literature review on hot ductility,[10] the transformation to ferrite and pearlite generally improves ductility in low carbon steels. It promotes the rapid precipitation of AlN which, for the long time periods involved, would produce precipitate coarsening. Reheating then nucleates new austenite grains that trap the coarsened nitride precipitates harmlessly inside. Further evidence that this tensile stress fails to initiate cracks at the surface is the lack of significant oxidation over most of the crack length. In addition, the magnitude, duration, and time delay for this tensile peak, while it is at the surface, are independent of the prior track time experienced, contrary to the incidence of panel crack formation. Finally, if a surface tensile stress fails to initiate cracks during air cooling, then it is unlikely to do so during reheating either, since the maximum tensile stresses attained are actually lower.

As was shown earlier,[8,9] this tensile peak quickly moves completely beneath the ingot surface and proceeds toward the corner as it moves deeper. After 20 minutes, the tensile zone has moved completely below the ingot surface and has assumed a sausage shape that extends from just below the center of the narrow face, around beneath the off-corner region, and part way along the wide-face. As the third tensile peak moves completely beneath the surface it encounters steel that has remained in the two-phase region for a significant length of time. At this stage, it clearly becomes the most influential stress factor in the generation of off-corner panel cracks.

From calculations based on the precipitation thermodynamics of AlN,[11,12,13] it was determined that the locations likely to suffer the most detrimental nitride precipitation are those which just barely drop below the Ar_3 temperature and stay in this temperature range for 30 minutes to 1 hour before reheating. Longer than this or lower temperatures result in precipitate coarsening and improved ductility, while less time or higher temperatures is insufficient for significant precipitation. For the conditions of the present simulation this zone of worst embrittlement appears to be centered around 50 mm beneath the surface point being tracked at the "off-corner subsurface location" (see Figure 2).

When the embrittlement is combined with the stresses of the third tensile peak, which reach nearly 10 MPa and are oriented across the grain boundaries, subsurface cracks might initiate. The high shear strains that accompany the preceding compressive band would undoubtedly add to the likelihood of subsurface cracks. In addition, the shape attained by this subsurface tensile region corresponds closely to the ultimate location of off-corner panel cracks reported by Sussman et al.[4] and illustrated in Figure 1. Further evidence that this tensile peak is responsible for the initiation of off-corner panel cracks can be gathered through examination of the influence of important parameters of track time and reheating rate, which will be done in the next sections.

Assuming that subsurface cracks can form during the third tensile wave, they are prevented from immediately propagating back through to the surface for two reasons: (1) the

surface has, at this time, fallen back into compression and (2) the surface, being below the Ar_1 temperature, should have improved ductility for the reasons stated earlier.

Later during reheating, a fourth tensile peak is experienced because as internal temperature gradients subside, the resulting relative expansion of the interior of the ingot forces the surface of the wide face into mild tension. This first occurs (after about one hour of reheating) at the off-corner surface location, as shown in Figure 10. The tensile region penetrates only a short distance beneath the ingot surface, but it persists for many hours of reheating while creep relaxation diminishes its magnitude. Sussman et al.[4] attribute the propagation of the subsurface cracks through to the surface to this phenomenon.

Embrittlement caused by nitride precipitation during reheating might allow an internal crack to penetrate through the surface, when combined with stress concentration at the tip of the pre-existing crack. In addition, with long times at high temperatures, abnormal grain growth might occur, especially if the grain coarsening temperature had been exceeded, thereby allowing detrimental secondary recrystallization and potentially even local grain boundary melting if the surface temperature became excessively high.

However, the results of the stress model indicate that plastic creep relaxation diminishes the magnitude of the stresses considerably with increasing time during reheating. Although this produces large inelastic strains of 2 to 5 pct near the surface, these should be insufficient to cause fracture without severe embrittlement or strain concentration. Since these stresses relax even further with increasing time, the cracking tendency would be expected to decrease with increasing time in the pit, if stress generation were the sole determining factor. However, many previous studies have observed the incidence of off-corner panel cracking to increase with increasing time in the soaking pit. Evidence from the present metallurgical investigation, finding only a very thin oxidized region, also tends to dispute the formation of panel cracks during the first few hours of reheating. Thus, any cracks that propagate through to the surface likely do so during the latter stages of reheating from primarily metallurgical phenomena.

Immediately after removal from the soaking pit, a fifth tensile peak sweeps rapidly over the ingot surface. This peak arises due to the rapid contraction of the quenched austenitic surface in a similar manner to the generation of the first tensile peak, experienced after stripping from the mold. The only major difference is the higher absolute stress level and longer duration of the fifth peak. If the reheating conditions were such that grain boundary embrittlement or severe grain growth had occurred, then these tensile stresses would very likely concentrate strain at the austenite grain boundaries and propagate any subsurface cracks through to the surface. Coarse grains would aggravate this type of embrittlement by enhancing strain concentration at the austenite grain boundaries.[14] Moreover, since the nitrides would have redissolved during reheating, their reprecipitation might embrittle the surface at the time when stresses were a maximum and the temperatures were just above the Ar_3.

Thus, off-corner panel cracks most likely propagate to the surface just after removal from the soaking pit. If shallow surface cracks had been previously initiated by the first or second tensile peaks, then the subsurface cracks would naturally link together with them. The majority of the elastic

strain might then be taken up by the formation of a single, intergranular crack, most probably located in the off-corner region. The rest of the subsurface cracks might then close under surface compression during the latter stages of air cooling. This is the proposed sequence of events experienced by the ingot shown in Figure 2. If a single crack could not form to relieve the tension, then a band of subsurface cracks similar to those found by Sussman et al.[4] in Figure 1 would likely result.

Following the fifth tensile peak is a compressive band and then the sixth and final tensile peak. Under ordinary circumstances, rolling would have already occurred, opening up the off-corner panel cracks to make them easily visible and culminating in the scrapping of the partially rolled ingot. However, the ingot analyzed in the metallurgical investigation had been allowed to cool completely through this sixth tensile peak. Because the grain boundaries had already been severely weakened, further cracks were generated and superimposed on the major cracks existing previously. These cracks naturally had no decarburization and traversed the ferrite/pearlite structure, in a manner similar to mid-face panel cracking since they formed during the tensile peak arising between 500 °C and the Ar_1 temperature. They naturally followed the path of least resistance which was the pro-eutectoid ferrite bands commonly arising in steels of this carbon content.

Ultimate cooling to ambient temperature places the interior in tension, further propagating narrow cracks from the roots of the major decarburized cracks deeper into the ingot. The compressive stress at the surface may close up existing panel cracks, which renders them more difficult to detect.

The importance of the off-corner location, where cracks are ultimately found, appears to be mainly a geometric effect associated with the aspect ratio of rectangular ingots. However, the presence of corrugations influences the local variation of stresses in the ingot surface. The highest stresses were generally found either directly beneath the corrugation peaks or at the surface in the corrugation troughs which also experienced the highest inelastic strains.[9] Thus, cracks initiating in the higher stress region beneath a corrugation peak might bend toward a corrugation trough while propagating outward to the surface. This would give rise to the crack pattern observed in the sample in Figures 2 and 3. While the presence of mold corrugations likely does not influence whether or not panel cracks develop, the results indicate that they may influence the precise location at which they appear.

Having established the major characteristics of stress development in a typical ingot and linked it to temperature development and susceptibility to embrittlement and crack formation, the results from additional simulations will be examined that explore the influence of the two most important operating variables: soaking pit reheating practice and track time. Attention will focus on the critical subsurface tensile region that arises beneath the corner of the ingot during the early stages of reheating.

A. Effect of Track Time

The simulation central to this study assumed a typical "track time" of 5.75 hours, including 1.75 hours of air cooling. Previous industrial experience indicates that long track times (over two hours for this ingot size) may reduce the

incidence of off-corner panel cracks.[3] Alternatively, very short track times, achieved by stripping the ingot from the mold early and quickly transferring it to the soaking pit has been suggested as a remedy.[4,15] Thus, to explore the effect of this important variable, additional model simulations were conducted that include both a shorter air cooling time of 1.25 hours and a longer air cooling time of 3.0 hours. Each of the simulations employed the same less severe reheating schedule: charging to a soaking pit initially at 650 °C, then increasing the pit temperature linearly to 1300 °C in three hours.

Figure 11 presents the temperature contours calculated by the heat-flow model during cooling, at the time of charging to the soaking pit for these three cases. In the figure, the Ar_3 isotherm of 780 °C corresponds to the center of the band of most severe embrittlement, and the phase transformation zone between 780 °C and 650 °C outlines the re-
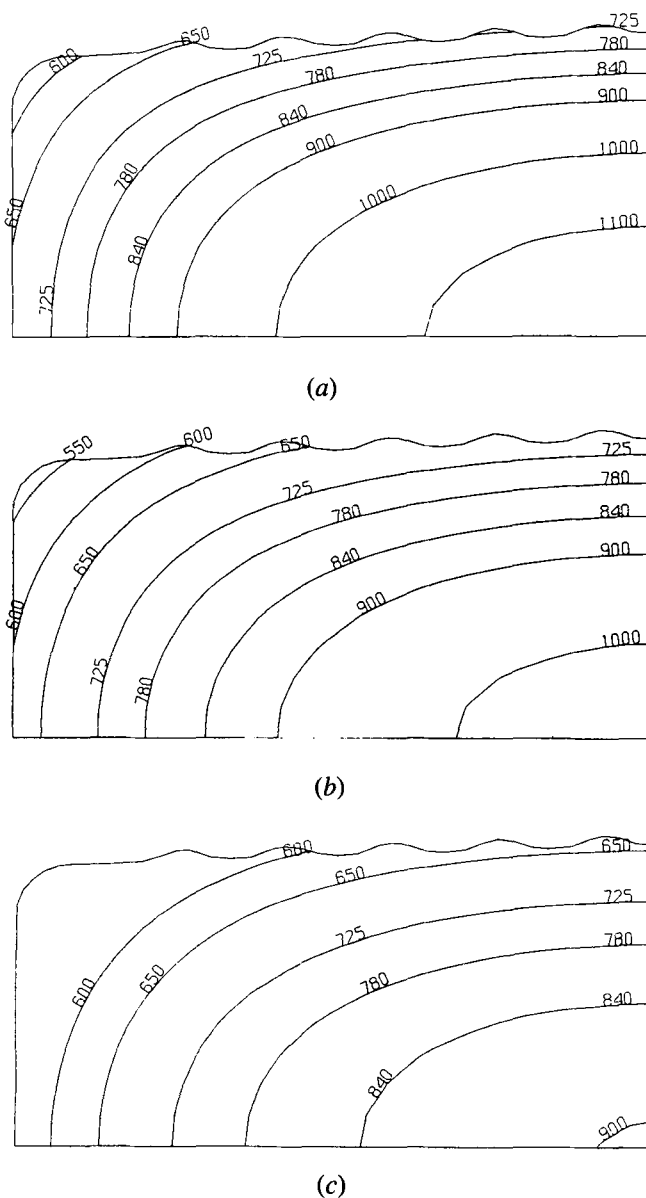

(a)

(b)

(c)

Fig. 11 — Temperature fields arising in 760 × 1500 mm ingot at time of charge to soaking pit after three different air cooling times: (a) 1.25 h after stripping (18,900 s), (b) 1.75 h after stripping (20,700 s), and (c) 3 h after stripping (25,200 s).

gion calculated to be under compression. Figure 11(c) shows that the entire surface of the ingot has fallen well below the Ar_1 after three hours of air cooling. Consequently, the ingot surface is under tension upon the start of reheating, although the completely transformed structure should have good ductility.

The temperature and stress contours that develop from these three conditions early during reheating are presented in Figure 12. In each case, the times chosen during reheating correspond to the critical time when the off-corner subsurface location reaches the Ac_3 temperature of 840 °C. At this position, the subsurface band of tension has just moved completely below the ingot surface and reached its maximum extent. It has also just passed beneath the off-corner, subsurface location, 52 mm beneath the first corrugation trough. Naturally, the time during reheating at which this

event occurs increases (from 50 to 75 minutes) with increasing air cooling time (from 1.25 to 3 hours). As the track time increases, the temperature predictions show that the amount of two phase material enclosed by the retransformed surface layer, marked by the 840 °C isotherm, both increases (reflecting the higher temperature gradients) and moves farther away from the vicinity of the corner. As shown by the stress contours, this causes the subsurface band of tension to move deeper below the corner and spread farther along the wide face with increasing track time. This behavior of the position of the subsurface tensile zone is remarkably similar to that of the bands of off-corner panel cracks which were found by Sussman et al.[4] to lie deeper within ingots which had experienced longer track times.

The zone of worst embrittlement should correspond roughly to the maximum penetration of the Ar_3 contour
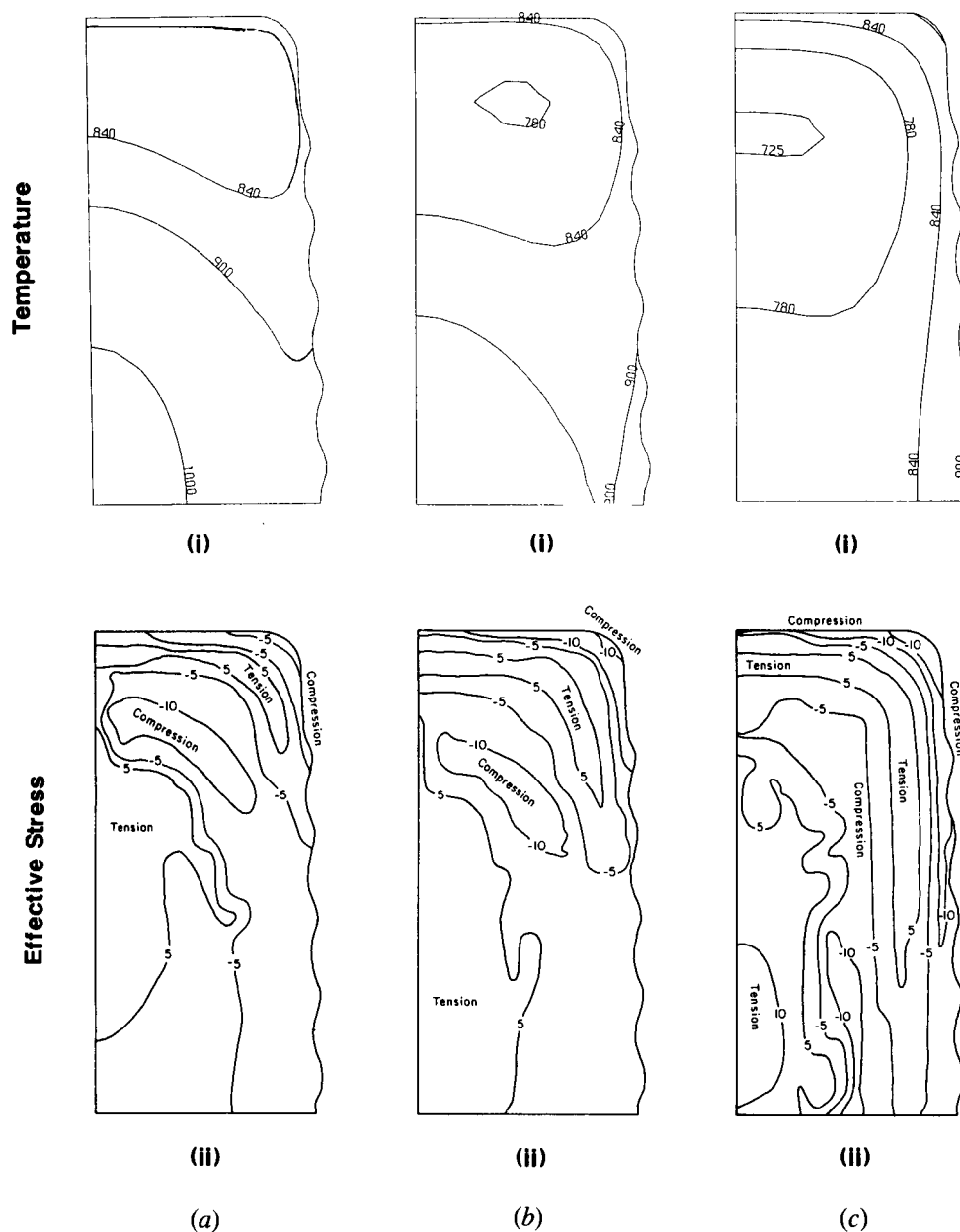

Fig. 12—Effect of track time on temperature and location of subsurface tensile region during reheating. (a) Conditions after 1.25 h air cooling and 50 min reheat (21,900 s), (b) conditions after 1.75 h air cooling and 60 min reheat (24,300 s), and (c) conditions after 3.0 h air cooling and 75 min reheat (29,700 s).

line of 780 °C, which occurs shortly after charging. An examination of this contour with respect to the position of the subsurface tensile zone shows that the tensile region consistently lies closer to the ingot surface and only barely overlaps. Thus, panel cracks should be expected to be relatively rare and arise only under cases of extreme embrittlement when material held near the Ar_3 temperature is weakened sufficiently to be affected by the tensile stresses.

The temperature and normal stress histories of the important off-corner subsurface location are traced in Figure 13 for the three different track times under investigation. This figure clearly shows that the period of tension experienced by a location beneath the ingot surface corresponds almost exactly to the time spent within the temperature region between just above the Ac_1 and the Ac_3 temperatures while the retransformation to austenite produces contraction.

The critical tensile peaks at this location develop about 30 minutes after their corresponding peaks at the ingot surface. The peak for the short air cooling time is smaller than the others and fails to become tensile, owing to the rapid migration of the tensile zone upward toward the corner, bypassing the vicinity beneath the first corrugation. Although they arise at different times, the magnitude and breadth of the tensile peaks for the longer two track times are quite similar, indicating that any differences in cracking tendency between these two cases must be due, primarily, to a difference in metallurgical integrity. Note, in this regard, that the temperature for the case of 3 hours air cooling falls below the Ar_1 before reheating, while the 1.75 hour case remains within the two-phase temperature range near the Ar_3 for over two hours. This should improve the relative resistance to crack formation in the longer track time case, for the reasons previously discussed.
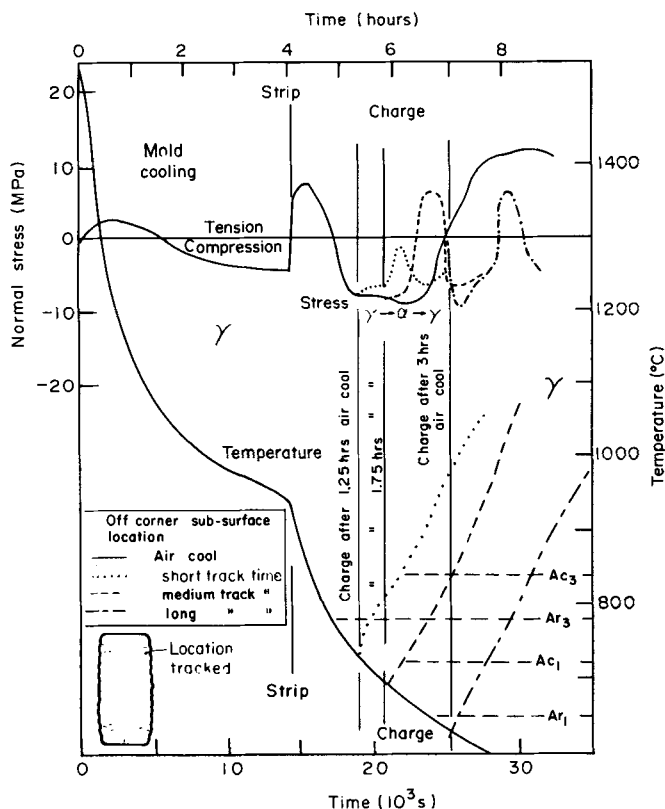
Finally, a very short track time was simulated by stripping the ingot after only 3 hours of mold cooling and charging to the soaking pit after only 0.5 hours of air cooling. Figure 14 shows the resulting temperature and stress histories at both the surface and subsurface locations. The temperature curves show that this portion of the ingot (like most of the remainder) stays above the Ar_3 throughout the entire process. This has the profound effect of maintaining compression both at and within the ingot surface throughout reheating, thereby avoiding the subsurface tensile stresses responsible for initiating panel cracks. This finding confirms previous hypotheses that reduced track times are beneficial, and points to an effective means to avoid panel cracking. The results of this examination of track time variations reinforce the previous finding that the subsurface tensile stress arising early during reheating is responsible for initiating subsurface cracks.

B. *Effect of Reheating Schedule*

Several previous researchers have reported that the incidence of off-corner panel cracks can be reduced by charging susceptible ingot grades into an initially cold soaking pit[3,15,16] and/or by employing a slow, controlled heating rate.[16] To investigate the effect of reheating rate on stress generation and panel crack formation, simulations were conducted for the three different reheating schedules illustrated in Figure 15. The first simulation followed a relatively rapid reheating schedule (No. 1). The second reheating schedule was less severe and assumed an initial cold pit of
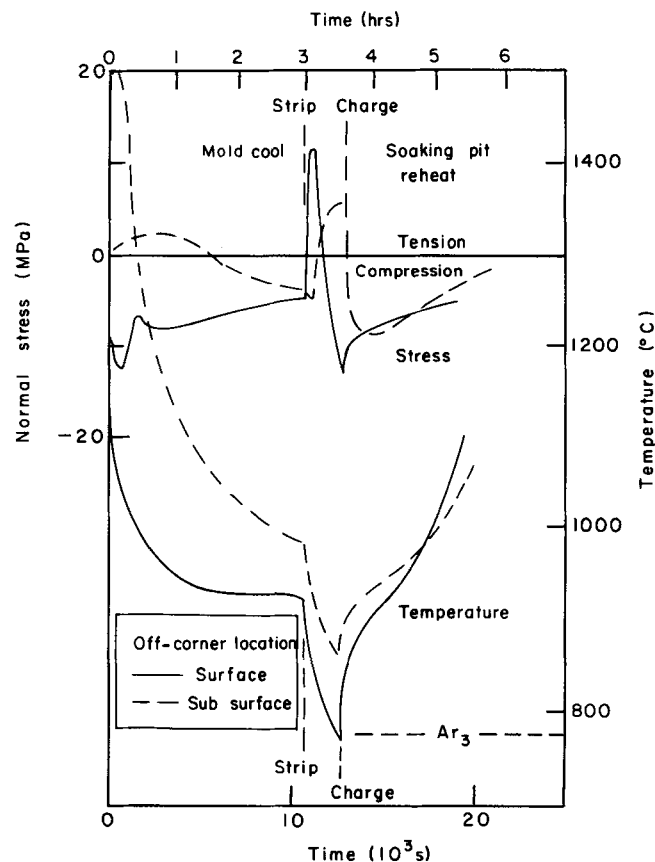

Fig. 13 — Influence of track time on the thermal and stress histories of the off-corner subsurface location during processing of a 760 × 1520 mm ingot.

Fig. 14 — Thermal and stress histories at off-corner locations during processing with very short (3.5 h) track time, including 30 min air cooling.
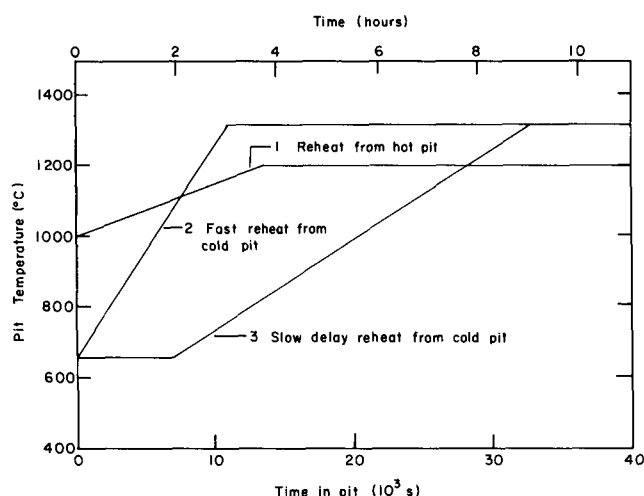
Fig. 15 — Soaking pit reheating schedules simulated in model.

650 °C. These were the conditions applied in the previous calculations on track time. The third reheating schedule was designed to model slow, controlled reheating; an initially cold (650 °C) pit was maintained for two hours prior to reheating slowly to 1315 °C over 7 hours.

Figure 16 presents the predicted temperature and normal stress histories of the off-corner, subsurface location during reheating for each of these three different reheating conditions. All three simulations employed the detrimental
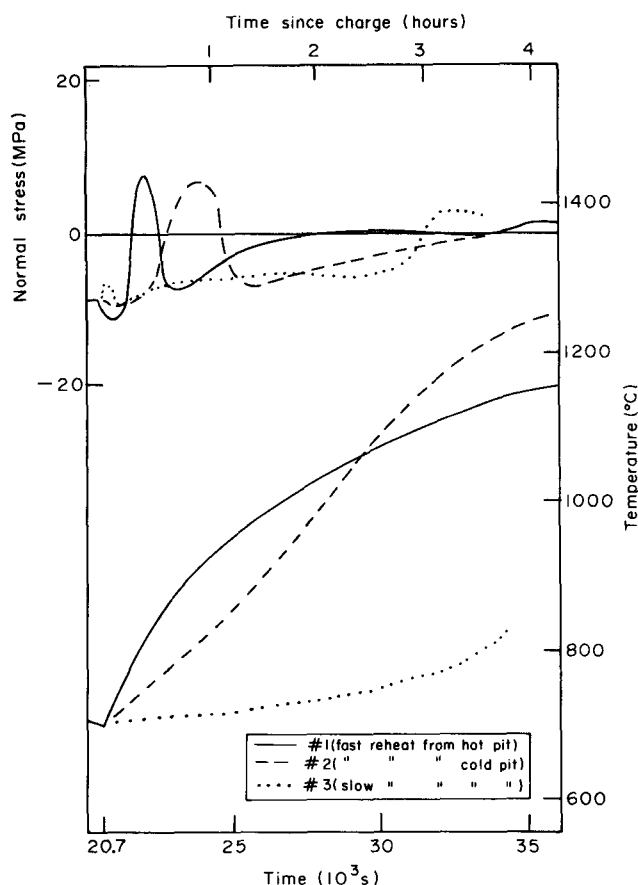

Fig. 16 — Effect of reheating practice on the thermal and stress histories during reheating at the off-corner subsurface location, after 4 h of mold cooling and 1.75 h air cooling.

track time of 5.75 hours, including 1.75 hours of air cooling. This figure shows that all three cases exhibit the same essential features, with the time frame extended as the ingot reheating rate decreases and a longer time is required to reach the transformation temperatures. The first, greatest tensile peak (responsible for initiating subsurface cracks) becomes broader and lower in magnitude as the heating rate is decreased, corresponding to the longer time spent between the Ac_3 and Ac_1 temperatures. The second tensile peak arises much later and persists for a longer time, but is much less severe. Since it takes over 4 hours to develop for the slower reheating rates, this tensile peak is not shown for the last two runs.

The most important observation is that this sequence of two tensile peaks apparently cannot be avoided, so long as the surface has cooled below the Ar_3 by the time of charging. However, the time of their occurrence can be delayed through slow or delayed reheating practices, thereby allowing increased creep relaxation which produces tensile peaks that are somewhat diminished in magnitude.

V. MECHANISM OF CRACK FORMATION

Off-corner panel cracks clearly develop in a much more complex manner than do mid-face panel cracks. The results of the mathematical simulations, metallurgical investigation, and prior research together suggest a consistent mechanism for off-corner panel crack formation that involves three separate stages. The mold is not a factor because any subsurface tension developing during solidification before stripping can be accommodated easily by creep strain relaxation, owing to the excellent ductility of steel above 1100 °C.

(1) During air cooling, shallow surface cracks may initiate near the off-corner region from high tensile stresses combined with lower ductility via the same mechanism that causes mid-face panel cracks.

(2) Rapid reheating of the ingot surface following a critical amount of air cooling results in the enclosure of a region of two-phase steel beneath the surface near the corner that is heating and contracting within a narrow zone of retransformed expanding austenite (Figure 12). This results in a temporary, subsurface tensile region, whose location near the corner, and shape, corresponds closely to the eventual location of off-corner panel cracks. Subsurface cracks are likely to initiate here at this time because steel in the temperature range just above the Ar_1 is susceptible to embrittlement by nitride precipitation at the austenite grain boundaries. The behavior of this tensile zone with varying track time and reheating practice corresponds closely to the observed behavior of off-corner panel cracks. They both disappear with very short track times but with longer track times, move deeper below the ingot surface and away from the corner. In addition, the appearance of this tensile zone is delayed and its magnitude is diminished with slower or delayed reheating conditions.

The lack of extensive decarburization found on the crack surface suggests that the cracks do not propagate through to the surface at this time. This is because the thin surface layer of retransformed austenite is both under compression and has better ductility, after trapping the aluminum nitride precipitate harmlessly within new grains.

(3) The final stage of propagating the subsurface cracks through to the surface or linking them with existing surface cracks (from stage 1) does not occur until later during reheating, or more likely, during air cooling following removal of the ingot from the soaking pit. This mechanism is similar to that proposed by Sussman[4] and explains many previous findings and observations regarding off-corner panel cracks.

VI. SOLUTIONS TO THE PROBLEM

The mechanism proposed for the formation of off-corner panel cracks suggests several alternative methods for alleviating the problem. They may be classified into three general approaches. The first approach is to prevent the subsurface band of cracks, corresponding to the critical subsurface tensile zone, from forming during the early stages of reheating. This can be achieved most effectively by employing a very short track time that keeps the entire ingot in the purely austenitic range above the Ar_3 temperature at all times prior to drawing the ingot from the soaking pit. The stress model results show that such a cooling practice completely eliminates this detrimental, third tensile peak. Unfortunately, this beneficial practice is often unachievable due to logistical constraints.[3]

A second, less optimal solution is to employ a long track time that forces the subsurface cracks to initiate very deep within the ingot. If the subsequent fifth tensile peak, on removal of the ingot from the soaking pit, fails to force cracks through the thicker exterior of uncracked steel, then the internal cracks will eventually close during rolling. Unfortunately, this practice is unreliable because stress prior to reheating increases with increasing track time, potentially producing even deeper off-corner panel cracks. In addition, it is difficult to implement because:

(1) effective track time constraints should depend on factors influencing cooling rate such as ingot size and mold cooling time;

(2) each ingot in the heat experiences a different thermal history.

Another way to reduce the extent of the critical subsurface tensile peak is to implement a slow, delayed reheating schedule from an initially cold pit. This delays the third tensile peak, thus providing additional time for nitride precipitate coarsening, and reduces the stress levels. However, the stress model predictions show that, even for this most favorable reheating schedule, a subsurface tensile band still develops eventually, if the track time was unfavorable. Simply reheating from an initially cold pit produces only a slight reduction in the third tensile peak. This solution would therefore not be expected to be as effective as proper track time controls.

The second approach to prevent off-corner panel cracks, suggested by the results of this work, is to prevent subsurface cracks that have formed, from propagating through to the surface. Since nothing can be done to prevent the surface tensile stresses from arising upon removal of the ingot from the soaking pit, this can be achieved only by avoiding metallurgical problems during the latter stages of reheating. To do this, the internal soaking pit temperature should be controlled and prevented from becoming too hot. Ingots should be left in the pit for as short a time as neces-

sary to reheat and homogenize them prior to rolling. Excessive time not only aggravates ductility problems but wastes thermal energy. Attention should also be paid to the placement of ingots to ensure that none of their faces is overheated.

The final solution is to employ steel compositions that are less susceptible to ductility problems. This unfortunately risks compromising final properties such as impact strength since the mechanisms for embrittlement and grain refinement are the same.

VII. SUMMARY AND CONCLUSIONS

When combined with the findings of a metallurgical investigation of off-corner panel cracks, the predictions of heat-flow and stress models confirm the mechanism of crack formation. As in the case of mid-face panel cracks, the off-corner cracks are strongly associated with the γ-α phase transformation, but arise primarily during reheating of ingots in the soaking pit. Depending on the rate of reheating, an internal tensile zone develops shortly after charging as a band of two-phase material contracts while reheating within a surrounding framework of expanding austenite. This initiates subsurface cracks along the prior austenite grain boundaries in the off-corner region; the depth of the cracks depends on the air cooling time prior to charging. The strong, retransformed austenitic exterior which is under compression prevents the cracks from penetrating the surface at this time. Later during reheating, the relative expansion of the interior accompanying the leveling off of internal temperature gradients produces a slight stress in the exterior of the ingot. However, the rapid creep relaxation at these temperatures reduces the stress level of this tensile peak, thereby reducing the likelihood of crack-formation in the latter stages of reheating. Immediately upon exit from the soaking pit, the rapid cooling contraction of the austenitic exterior of the ingot produces high surface tensile stress. Strain concentration at the grain boundaries of enlarged austenite grains in combination with nitride reprecipitation allows the internal, off-corner panel cracks to propagate through to the surface.

The results of this work suggest several different measures to minimize off-corner panel cracks:

1. Prevent the stresses responsible for the subsurface cracks from developing during the early stages of reheating either by employing a short air cooling time or by reheating slowly from an initially cold pit.
2. Force the subsurface cracks to form deeper inside the ingot, so that they are unable to penetrate the surface, by employing a longer air cooling time.
3. Prevent the final air cooling stresses from propagating the subsurface cracks through to the surface by improving the ductility of the steel. This could be achieved by employing carefully controlled soaking pit practices that avoid excessive times and temperatures or by casting less susceptible steel compositions.

ACKNOWLEDGMENTS

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