The Formation of Panel Cracks in Steel Ingots: A State-of-the-Art Review

II. Mid-Face and Off-Corner Cracks

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ABSTRACT

In the second of this two-part paper the available literature on panel crack formation in steel ingots is reviewed. The panel cracks are observed at two locations - the mid-face and off-corner - in ingots. The characteristics of the two types of panel cracks are described and the mechanism of crack generation, as well as proposals for elimination of the defects, are presented. Both crack defects are caused by a combination of reduced low- and intermediate-temperature ductility associated with AlN embrittlement and stress generation due to changing thermal gradients and phase transformation. Practical solutions include altered steel composition or thermal treatment of the ingot.

INTRODUCTION

In the light of an increased knowledge of the ductility of steel at elevated temperatures, the studies made on panel cracking in static-cast, steel ingots will now be examined. During the late 1950's, at least four studies[1-4] were done on panel cracking, which was a well-known problem even at that time. Then, in the late 1970's, at least ten more studies into panel cracking were undertaken by major steel companies from seven different countries.[5-14] The cracking defects described in these studies can be classified into two distinct types.

The first was experienced by all of the early workers[1-4] as well as in several of the recent studies.[5-8] It was found exclusively in small ingots less than six tons, and affects only medium-carbon, aluminum-treated steels with 0.4 - 0.7 percent C or 0.3 - 0.6 percent C if either 1 percent Cr, Ni or Mn is present. This problem is usually manifested by a single, continuous, longitudinal crack down the center of one of the ingot faces and, therefore, will be referred to as "mid-face panel cracks."

Most of the recent studies involved a distinctly different kind of panel cracking,[9-14] although several companies have experienced difficulty with both types.[6,8] The second type of panel crack is mainly experienced in much larger ingots ranging in size from 20-35 tons.[9-11,13,14] Unlike mid-face panel cracks, it only affects low-carbon steels. (0.1 - 0.2 percent C) with manganese contents above 0.7 percent.[9-14] The cracks are short and discontinuous, but quite deep (30-130 mm), having both transverse and longitudinal components.[9,12,14] They most often occur in bands near the edges of the wide face of the ingot and, therefore, will be referred to as "off-corner panel cracks."

MID-FACE PANEL CRACKS

Figure 1 presents a picture of a billet exhibiting a mid-face panel crack which runs down the center of one face. The cracks can extend to a depth of up to half the billet diameter and, depending on the severity, as many as three of the four faces can be affected.[1,3,4] On duo-decagonal ingots, the cracks run longitudinally down the center of the flutes. This is illustrated in the transverse ingot cross sections in Figure 2, which also show how cracks are sometimes found below

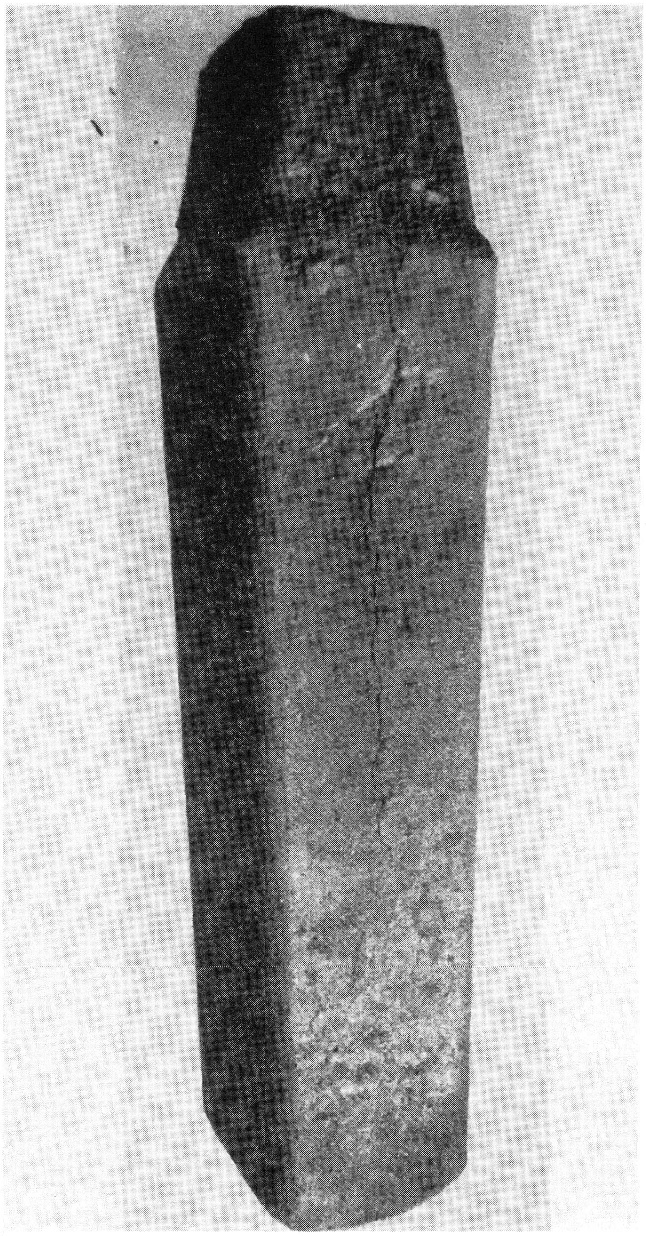

FIG. 1. Mid-face panel crack in 350 × 350 mm square En18 (0.4 percent C, 1.0 percent Cr) steel ingot.[1]

the surface of the billet face but do not extend to the exterior. This suggests that cracks may initiate internally and then propagate outwards. The defects are usually discovered either in the melt shop after stripping or during subsequent rolling operations. The extent of the defect varies from only one or two ingots being affected to entire heats being scrapped.

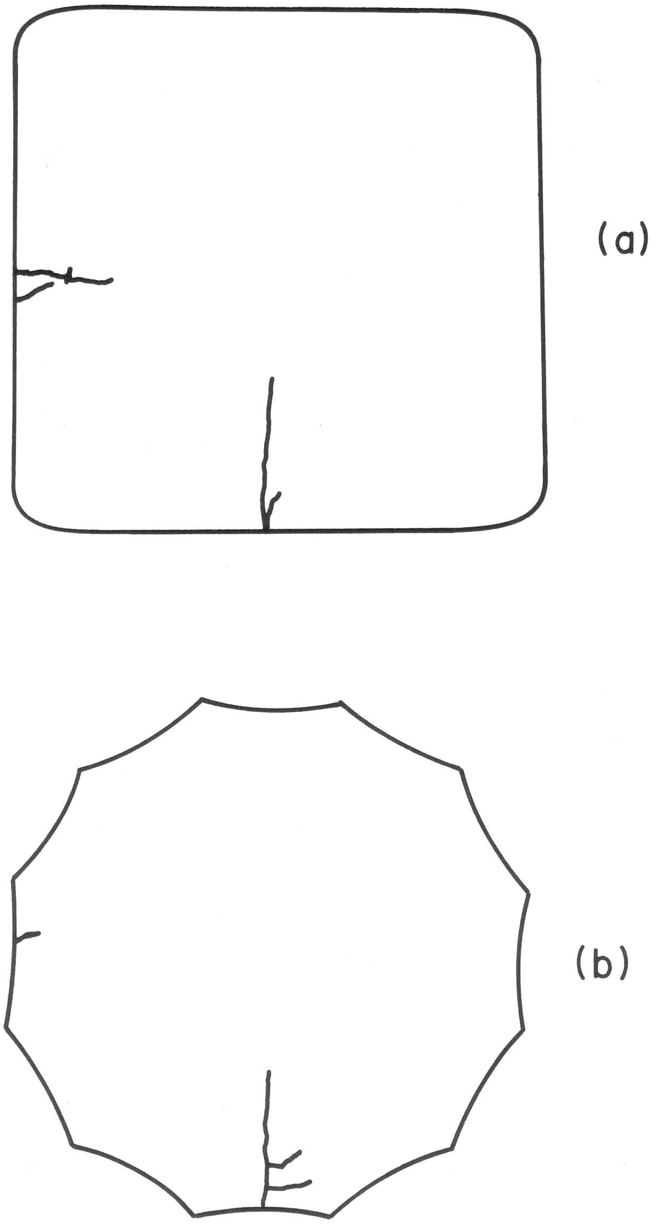

FIG. 2. Typical location of mid-face panel cracks in a transverse cross-section of a:
(A) 370 mm square, 0.55 percent C, steel ingot[1-3]
(B) 380 mm duodecagonal, 0.6 percent C, steel ingot[3]

Metallography

All of the studies of mid-face panel cracks report that the cracks appear to follow the ferrite network between the pearlite grains along the prior-austenite grain boundaries. The fracture surface has long, curved, intergranular facets. Only slight, superficial oxidation of the cracks was observed[1,3-5] and no decarburization was present.[2,3]

Sulfur printing, macroetching, and chemical analysis revealed macrosegregation was not associated with the defects.[1-3] Furthermore, microscopic examination could associate none of the visible inclusions of stringers with the cracks.[1-3] Rarely do researchers report the presence of precipitates associated with the fracture in the grain boundary ferrite. Desai[3] found occasional manganese sulfide and alumina inclusions but only Ericson[7] reported finding AlN precipitates there.

It should be reemphasized here that particles are most damaging when they first precipitate and are very fine.[15-17] At this stage, their detection is very difficult. By the time they are readily identifiable, important events already may have occurred and the precipitates may have changed size, shape, location or effectiveness. Thus, grain boundary precipitation is always more severe than the examination methods suggest, and many workers could not find AlN precipitates even when ASA content clearly indicated high Al concentrations associated with cracking.[1,3,45]

Effect of Composition

As previously mentioned, mid-face panel cracking is confined to medium-carbon, hypoeutectoid, pearlitic steels with carbon content between 0.4 and 0.7 percent.[1-8] However, certain alloy steels containing either 1 percent Cr, 1 percent Ni or 1.5 percent Mn are particularly prone to this defect and are affected at slightly lower carbon contents.[1-3,5] There appears to be a lower limit of 0.3 percent C.[1,8] The addition of 0.2 - 0.3 percent Mo to the high Cr or Mn steels eliminated the cracking problem.[1,5] Guerin and Roccatagliata[5] reported a detrimental influence of Pb, Cu and possibly Sn.

Mid-face panel cracking only affects aluminum-treated steels and its incidence increases with increasing ASA up to 0.06 percent.[1-5,7,8] Steels with less than 0.015 percent[8] or more than 0.06 percent[1] experienced less problems. Little trouble was encountered with acid Open Hearth or "OH" steels, while basic OH steels were susceptible to cracking and basic electric arc steels were worse still.[1,8] Biggs[1] attributed the increased susceptibility of electric arc steels to their higher nitrogen contents (0.007 - .012 percent) compared with OH steels (0.004 - 0.006 percent). These facts imply that AlN precipitation is an important factor, if not the determining factor for mid-face panel cracks. Further evidence of this is the beneficial influence of titanium[1,3-5,7,8], V[3,5,8] and possibly Zr[5] in reducing the incidence of mid-face panel cracks.

Another interesting observation is that while steels forming both bainite and ferrite (in the form of grain boundary networks) are prone to cracking, fully bainitic steels are not.[5,7]

Effect of Ingot Size and Shape

Mid-face panel cracks are only found in small, two-six-ton ingots.[1-5,7,8] Guerin and Roccatagliata[5] summarized the experiences of five companies and agreed with two other studies[3,4] in concluding that mid-face panel cracking does not affect ingots smaller than two tons. They attributed this to the inability of very small ingots to generate internal thermal gradients during cooling sufficient in magnitude to cause stresses that result in cracking. No researcher has reported finding mid-face panel cracking in ingots larger than six tons.

Within this range, there is some disagreement as to the most susceptible ingot size. Ericson[7] found that two-ton ingots were more prone to cracking than six-ton ingots. Biggs stated that "intermediate sized" forging ingots were most susceptible and that panel cracking was rarely found in "very large" forging ingots.[1] However, Desai found that the cracking tendency increased with increasing ingot size above nine inches square.[3] Finally, others found cracks in the complete range of ingot sizes they produced.[4,5]

Ingot shape or mold design appears to be unimportant.[1] Mid-face panel cracks have been found in a wide variety of ingot shapes ranging from square, flat-faced billet to fluted, duodecagonal ingots.

Effect of Thermal Treatment

Mid-face panel cracking is independent of casting conditions such as teeming temperature and pouring rate.[1,4] However, the subsequent cooling practice is extremely influential. Ingots that are stripped from the mold hot and transferred directly to the reheating furnaces or subsequent forging operations rarely encounter cracking.[1-3] Ingots allowed to cool excessively are the most susceptible to cracking. Mid-face panel cracks are generally associated with long jacketed times[6,7] and/or long unjacketed times.[5,6] The lack of significant oxidation and decarburization in these cracks is evidence that they form at lower temperatures. Several researchers have proposed that mid-face panel cracks occur only after the ingot surface temperature has fallen below a critical value. This critical temperature is reported to be in the range of 550-700 °C[5,6] with an upper limit of 700 °C[2] or 850 °C.[3] It is suspected by some to be the Ar_1 temperature at the completion of the pearlite transformation.[8]

The cooling rate and symmetry of cooling may also be important. Mid-face panel cracks are reported to occur preferentially on the inside, high temperature faces between ingots that are too close to each other while cooling on the ingot buggy.[5,6]

In addition, stacking the ingots together or holding them in a preheated furnace to allow slower cooling was found to prevent cracking.[5] Guerin and Roccatagliata found that laying one face of the hot ingot on an insulating bed of vermiculite eliminated panel cracking as well.[5]

Reheating practice appears to be much less important. Only one study suggested that cracking was affected by the reheating rate.[8] Thus, although still not conclusive, mid-face panel cracking probably occurs during cooling.[5,6,8]

OFF-CORNER PANEL CRACKS

A photograph of an ingot affected severely by off-corner panel cracking is given in Figure 3. The majority of the defects are longitudinal, intergranular, discontinuous cracks near the edges of the wide face of the ingot. However, near the ingot extremities, particularly the bottom, they often begin to run in a more transverse direction, thus forming a rough oval pattern.[9,12,14] In addition, the ingot cross section in Figure 4 reveals a similar radial pattern of cracks just beneath the surface of both the narrow and wide faces.[9] Only those subsurface cracks that reach the surface cause rejects. In a corruguated ingot,

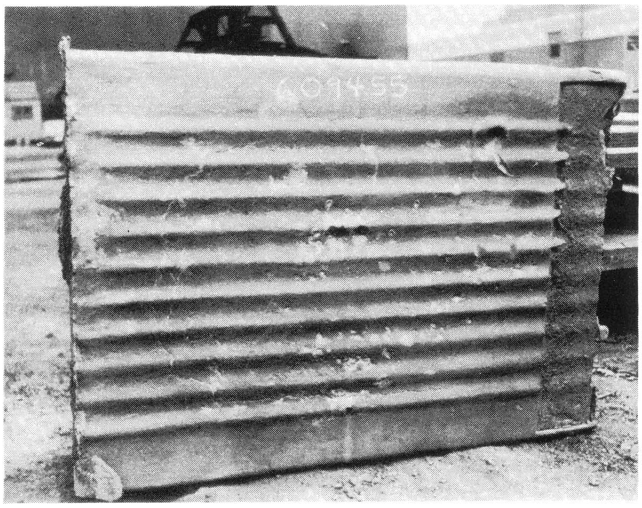

FIG. 3. Off-corner panel cracks in a 760 × 1520 mm, rectangular, corrugated (0.14 percent C, 1.4 percent Mn, Si-killed, Al grain refined) steel ingot.[14]

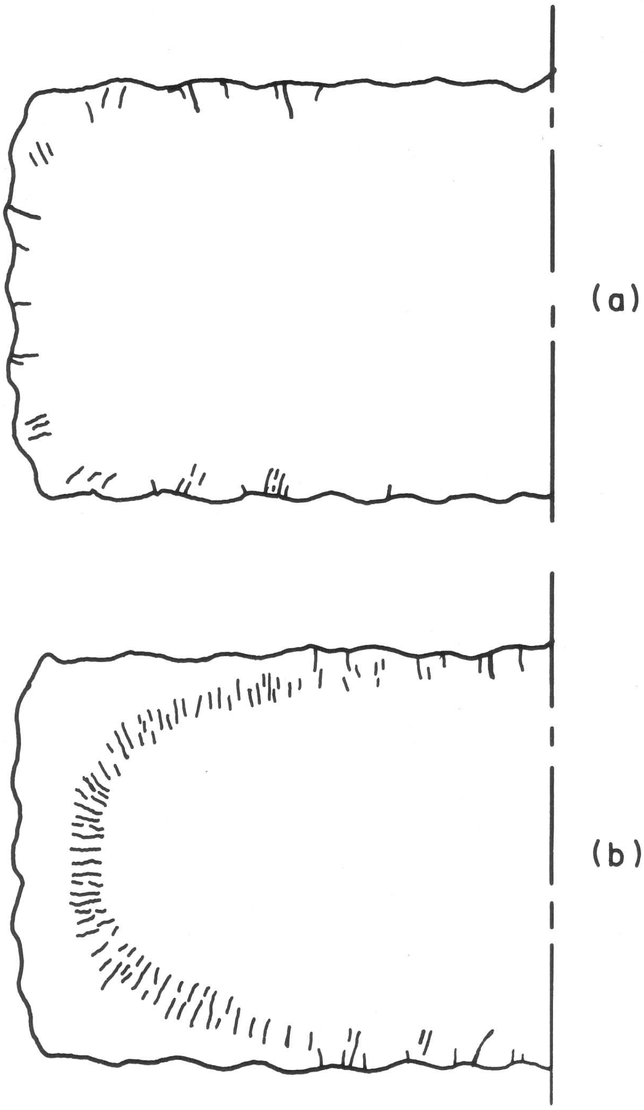

FIG. 4. Relative location of off-corner panel cracks found by Sussman[9] in transverse cross-sections taken from the top of ingots subjected to:
(A) 1260 s (21 min.) unjacketed time
(B) 6480 s (108 min.) unjacketed time

these damaging cracks are associated with the mold corrugations. Figure 5 shows how these cracks generally initiate directly beneath the peak of a corrugation, often the one nearest the edge of the wide face. They then bend to reach the surface at a point between the corrugation peak and an adjacent trough.[14]

The lack of cracking on the narrow face implies that rolling may close up subsurface cracks beneath the narrow face while it contributes to opening up those on the wide face.[9,14] The exact time of cracking between initial pouring and hot rolling is not known and various theories have been presented. However, the cracks are more associated with reheating since they are discovered, at the earliest, after removal from the soaking pit and usually are not detected until early hot working stages.[8] Like mid-face panel cracks, the extent of the defect varies from one ingot to the entire heat and affected ingots must be scrapped.

Metallography

Off-corner panel cracks are often found outlined with a thin ferrite zone which can be seen in Figure 6. Several researchers attribute this to decarburization.[6,9,12,14] Alternatively, some of the ferrite networks may have formed prior to cracking as in mid-face panel cracks. Figure 6 also shows that the ferrite zone associated with the cracks may contain several types of inclusions. These were found to be mainly large oxides of Fe, Mn, Si and Al[6,9,12,14] which were attributed to high temperature oxidation after cracking[9,12] or possibly during rolling.[12] An experiment done on two steel rings tightly screwed together to simulate a crack, confirmed that high temperature oxidation can penetrate the crack and preferentially oxidize the grain boundaries, producing oxide precipitates quite similar to those observed in off-corner panel cracks.[12]

In addition to the large oxides, very small (0.03 - 1.0 micron) precipitates containing Mn, Si, or Al were also found in the ferrite zone.[9,12] However, only a few workers actually confirmed the presence of AlN precipitates.[7,9] Negligible segregation of S, Mo or Cr was found[9,12] although one study found the ferrite zone depleted in Mn and Si.[12]

The crack may appear in two portions with the top quite wide, oxidized, and open to the surface, while the bottom appears welded shut.[14] One researcher also found evidence that recrystallization takes place after cracking.[6]

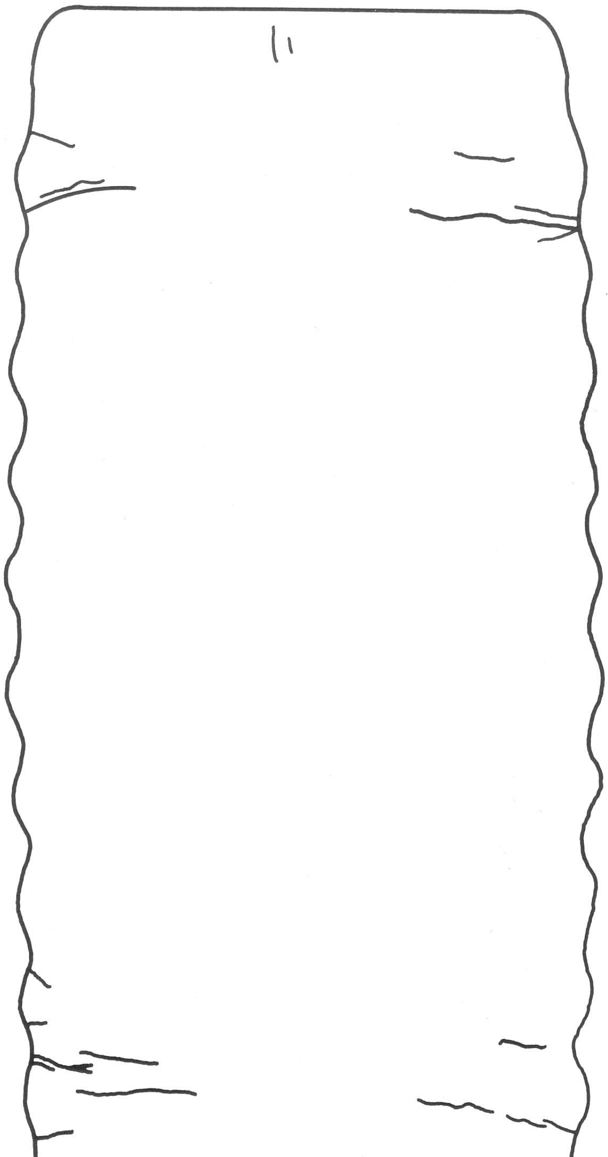

FIG. 5. Relative location of off-corner panel cracks in transverse cross-section taken from mid-height of a 760 × 1520 mm corrugated ingot.[14]

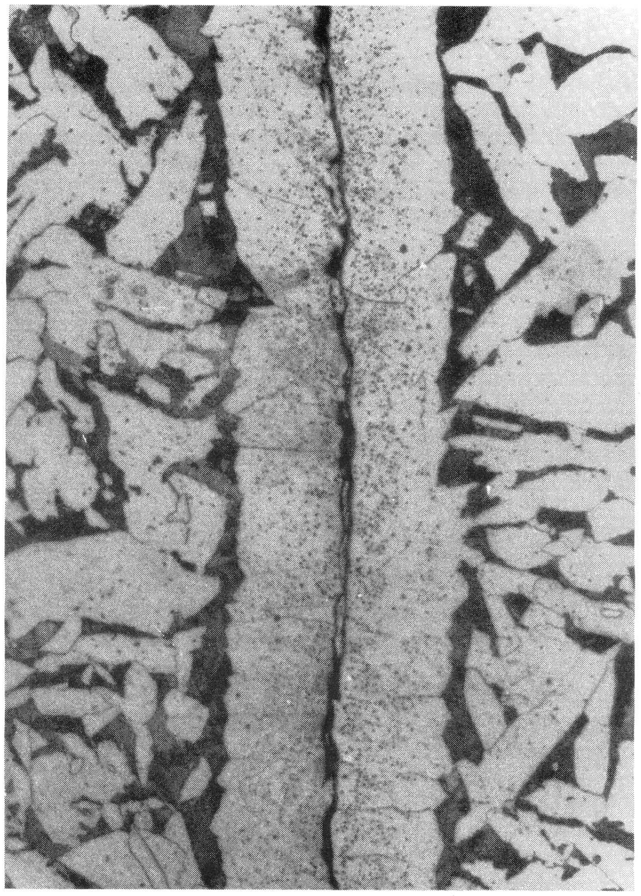

FIG. 6. Close-up of off-corner panel crack showing associated ferrite band and inclusions (etched in two percent nital, 120X).

Effect of Composition

As previously mentioned, off-corner panel cracks differ from mid-face panel cracks in that the former appear only in low-carbon steels (between 0.1 and 0.2 percent C)[6-8-14] with high manganese contents (> 0.7 percent Mn).[6,9,10,13,14] However, like mid-face panel cracks, the off-corner cracks are found only in Al-killed or Al grain-refined steels containing 0.015 - 0.6 percent ASA.[6,8-10,12-14] Some studies found the cracking incidence to be more likely with increasing ASA content[9,12,13] but other studies reported no particular trend with increasing ASA[6,10,14] so long as it was sufficient for grain refinement (> 0.015 percent ASA[12]). Off-corner panel cracks also have been associated with high N contents (> .007 percent N).[9,12,14] Thus, nitride precipitates and AlN in particular, are apparently conducive to both types of panel cracks.

Micro-alloy steels, containing Nb or V, were generally reported to be especially prone to off-corner panel cracking.[10,14] However, one researcher reported a beneficial effect of both Nb and V.[12] Increasing Cu above 0.3 percent may increase cracking susceptibility[12] while addition of Ti,[12] Zr,[10] or possibly Mo[10] all alleviate it. One company found off-corner panel cracks only in steels that contained Si.[14] No contributing effects were found for residual levels of H, Sn, As, Pb, Sb, O[12] and notably, S.[10,12] Most of the susceptible steel grades had low sulfur contents.[6,9,10,14] When combined with their high manganese contents, they consequently also had very high Mn/S ratios, usually greater than 50[9,10,14] and occasionally exceeding 200.[14]

Effect of Ingot Size and Shape

Off-corner panel cracks were mainly found in very large, rectangular ingots over 20 tons[9-11,13,14] such as the one pictured in Figure 3. However, they have also been found in ingots as small as only ten tons.[9,12,14] No particular trends with ingot size or shape have been noted except that cracking decreased with greater reduction ratios to slabs, presumably due to their partial closing during rolling.[9]

Effect of Thermal Treatment

Off-corner panel cracks are affected by cooling practice in a different way than mid-face panel cracks. Some studies again find that the incidence of cracking increases for long track times and occurs only when the track time exceeds 9000 to 21,600 seconds (or 2.5[8] to six[6] hours). Others find that off-corner panel cracks only appear when there has been a short unjacketed time, less than 7200 seconds (or two hours).[6,14] This is shown in Figure 7. Alternatively, short track times, less than 14,400 to 32,400 seconds (or four[8] to nine[6] hours) have been found to be the most detrimental. Ingots which were allowed to cool to ambient temperature before reheating never experienced off-corner panel cracking.

These conflicting observations have been rationalized with the explanation that the most harmful treatment is intermediate cooling that allows the ingot surface to fall into some critical temperature range before reheating.[6-9] Many researchers believe this critical temperature range to be the two-phase region between the Ar_3 and Ar_1 temperatures.[6,8,9,12] However, there is wide disagreement as to the actual cooling practice to be avoided. Another interesting observation is that the oval crack pattern observed by several researchers was found to displace towards the center of the ingot with increasing unjacketed time.[9,14] The oval crack pattern coincided closely with the location of isothermal contours that outline the boundary between the original warmer interior and cooler exterior. Thus, the cooling practice is obviously highly important in controlling the formation of off-corner panel cracks.

The majority of researchers agree that off-corner panel cracking is also greatly influenced by reheating practice, specifically, the reheating rate[8-14] and time[9,11,13,14] in the soaking pit. However, the same apparent contradictions and confusion about the effects of cooling practice also exist for reheating practice. Sussman found that cracking diminished for fast reheating rates and that the time spent between 650 and 1100 °C should be minimized.[9] Alternatively, several other researchers believe that slow, carefully controlled heating conditions minimize cracking.[10-12,14] Long times in the soaking pit are reported by some to be detrimental[9,14] but Nashiwa[11] states that a longer time in the soaking pit is beneficial.

PROPOSED MECHANISMS FOR PANEL CRACK FORMATION

Based on the findings of the numerous studies made on panel cracks, several attempts have been made at formulating mechanisms. There is general agreement that both forms of panel cracks are caused by a combination of the two factors: reduced hot ductility and stresses generated from thermal gradients and phase transformation. However, many researchers have only vaguely formulated mechanisms and the relative importance of these two factors is in considerable dispute.

Reduced High Temperature Ductility

One group of researchers believe that panel cracking is mainly due to a reduction in the hot ductility of steel.[1-4,7,8,12] In order to fail in an intergranular manner, the grain boundaries must be weakened at the temperatures where cracking occurs. The previous observations on the effects of thermal treatment imply that the lower temperature zone of reduced ductility, in particular the zone of embrittlement entirely below the A_1 temperature, is responsible for mid-face panel cracking. Ductility experiments done by Desai confirmed that steel from cracked ingots had lower ductility than uncracked ingots in the 600-700 °C range.[3]

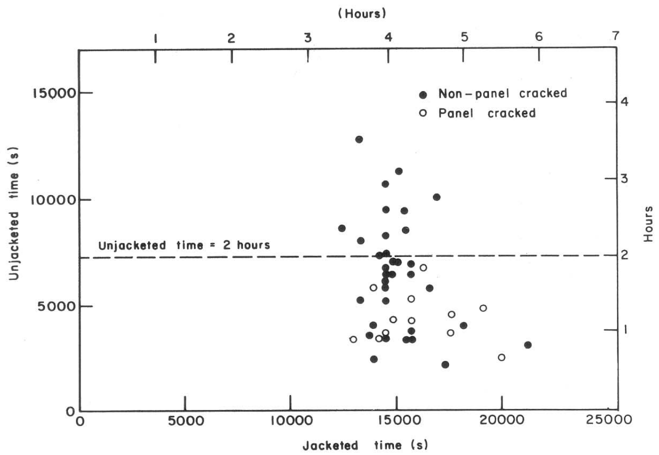

FIG. 7. The effect of cooling practice on the incidence of off-corner panel cracking.[14]

Although the intermediate-temperature embrittlement zone of steel is known to extend much higher than 900 °C, researchers attribute off-corner panel cracking solely to the low-temperature region between 700 and 900 °C. Their mechanisms are formulated in terms of AlN-precipitate pinning at the austenite grain boundaries. As previously deduced, this falls into either the low strain-rate zone of embrittlement in austenite involving the nucleation, growth and coalescence of grain boundary voids, or the lower-temperature embrittlement zone involving the two-phase region.

Mid-Face Panel Cracks

Two different explanations were postulated for the origin of the grain boundary weakness responsible for mid-face panel cracking. Biggs[1] and Colombo and Cesari[4] emphasized that the incidence of cracks increased with increasing aluminum and nitrogen contents. They argued that the grain boundaries were weakened mainly by the presence of mechanically weak, second-phase particles. As the solidified steel cools, the precipitation of fine AlN particles occurs at the austenite grain boundaries. These precipitates may persist to lower the ductility of the grain boundary ferrite, either before or after the pearlite transformation. Cracks would then tend to initiate at the weakened grain boundaries under the application of stress.

On the other hand, Irvine and Pickering[2] argue that the failure occurs at the grain boundaries due to the presence of thin, ferrite networks. Below the Ar_3 temperature, austenite first transforms to primary ferrite at nucleation sites in the grain boundaries. Then, as the steel cools below the Ar_1 temperature, the remaining majority of the austenite transforms to pearlite, leaving a harder and less ductile phase surrounded by the ferrite film. Under stress, the weaker, more ductile ferrite film is subjected to a disproportionate amount of strain and eventually fails in a ductile manner. This explains the presence of a ferrite zone outlining an intergranular crack network, and explains why the cracks only appear after long cooling times when the surface has dropped below the Ar_1 temperature. It suggests that a critical distribution or thickness of grain boundary ferrite might be involved[1,50] this being controlled by composition and cooling rate. This is supported by the observation that only certain carbon levels and thermal treatments were prone to panel cracking. This theory also accounts for the lack of cracking in fully bainitic steels or in Mo-bearing steels, where the pearlitic transformation is retarded.[7]

Since there is some evidence supporting each of the two mechanisms, all of these researchers admit that a combination of both mechanisms most likely accounts for the intergranular nature of panel cracking. Mid-face panel cracking is thereby explained by the slow nucleation of fine AlN particles preferentially precipitating at the grain boundaries. This further weakens the ferrite film network where subsequent stress and strain concentration results in an intergranular failure.

Off-Corner Panel Cracks

Several studies attribute off-corner panel cracking to the embrittling mechanisms that reduce the intermediate-temperature ductility of steel at low strain rates. A mechanism has been developed to explain the relationship between off-corner panel cracking and thermal treatment,[6,8] and is represented schematically in Figure 8. When track times are very short, the surface is prevented from falling into the two-phase region. Researchers subscribing to this mechanism believe that cracking does not occur in this case because of the resulting lack of embrittling precipitates.

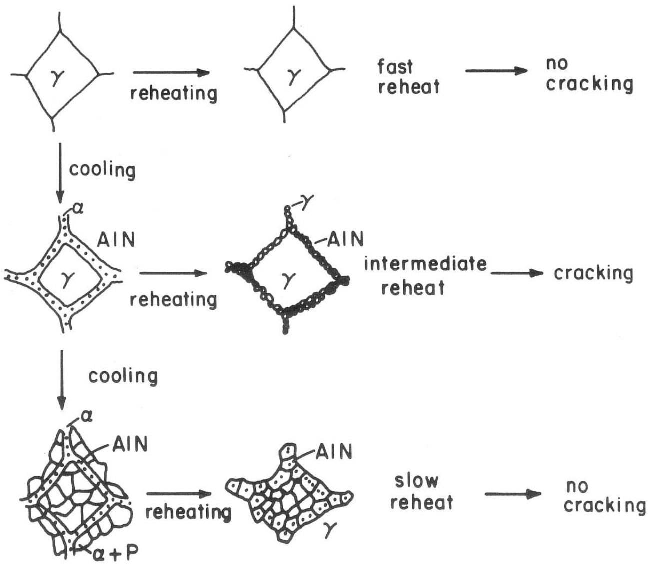

FIG. 8. Mechanism for formation of off-corner panel cracks involving reduced ductility.

At intermediate track times, the surface falls into the two-phase region, but does not go below the Ar_1 temperature. Thin ferrite films form at the austenite grain boundaries together with fine nitride precipitates such as AlN. Cracking then occurs along the weakened, ferrite networks during reheating or hot deformation.

For long track times, the surface completely transforms to ferrite and pearlite to a considerable depth. AlN precipitates again form at the grain boundaries. However, upon reheating, new austenite grains are formed when the surface retransforms and the dangerous chains of AlN precipitates are trapped harmlessly inside them. Thus, again there is no cracking.

Ericson[7] has suggested an alternate explanation for the particularly detrimental effect of Al on both types of panel cracking. As the ingot cools, Al may segregate preferentially to the austenite grain boundaries,[7,12] particularly in the oval boundary region separating the warmer and cooler areas of the ingot's wide face. The segregation of other ferrite formers (Cr, Mo, S, P, Si) may be enhanced as well. This segregation may be attenuated by the ferrite-austenite peritectic phase transformation.[6,8] Since an increased concentration of these elements will increase the Ar_3 temperature locally, this would promote the earlier formation of primary ferrite at the grain boundaries and in the oval area. Precipitates, particularly nitrides, then rapidly nucleate in the grain boundary ferrite. Combined with stress concentration in the ferrite film, a classic, intergranular, low-ductility failure occurs. Ericson[7] explains that slow even cooling, or long track times, reduce the cracking tendency by lowering internal temperature gradients. This results in less Al segregation and, therefore, no local ferrite formation or preferential precipitation.

Although the beneficial effect of Ti has been explained previously in terms of its preferential formation of coarser, more evenly distributed precipitates, Ericson believes that Ti helps prevent panel cracking in two additional ways. Firstly, it promotes a fine austenitic structure with low microsegregation after solidification by diminishing the solidification temperature interval. Secondly, it discourages ferrite network formation even though Ti itself is a ferrite former. It does this by reducing solid-state microsegregation of Al and by retarding the $\gamma \rightarrow \alpha$ transformation. This reduces mid-face panel cracking in bainitic steels by encouraging bainite formation, thereby preventing the formation of detrimental ferrite networks.

Stress Generation

Despite these convincing arguments for the hot ductility of steel being the determining factor for panel cracking, most of the previous observations can also be explained in terms of stress generation. A second group of researchers believe that panel cracking is due mainly,[9,10,13] if not entirely,[11] to thermal and phase transformation stress.

Mid-Face Panel Cracks

On the basis of two early studies,[2,3] a vaguely formulated mechanism for mid-face panel cracking due to stress generation has emerged. As the steel solidifies and cools, the soft center seeks to contract within a rigid outer framework. Thus, internal tensile stresses develop due to changing thermal gradients and phase transformations. The stresses were thought to reach a maximum at the center of the billet face where the panel cracks were ultimately observed. Under this stress, cracks initiate below the ingot surface at the austenite grain boundaries. This mechanism requires that the temperature is low enough at the time of crack formation that stresses are not relieved by plastic deformation. The cracks then propagate outwards as the steel continues to contract.

Other researchers[5,8] have refined this mechanism by considering the volume expansion that accompanies the $\gamma \rightarrow \alpha$ phase transformation in steel. They emphasize the previously discussed observation that mid-face panel cracking occurs when the surface falls below some critical temperature presumably connected with the $\gamma \rightarrow \alpha$ phase transformation. According to their mechanism, the billet surface is expanding during transformation while the austenitic interior is still cooling and contracting. A subsurface tensile stress consequently develops. Cracking occurs at this stage as the transformation front moves inward.

However, this mechanism is incomplete, since the warm, austenitic interior may be able to deform sufficiently through creep to avoid cracking until the surface drops below the Ar_1 temperature. As cooling proceeds, the fully transformed surface begins to contract again while the austenite transforming beneath the surface is still expanding. This puts the surface into tension while it is composed entirely of ferrite and pearlite. The zone of low ductility associated with precipitate-embrittled ferrite networks surrounded by pearlite results in cracking.

This mechanism suggests that steels with a narrow two-phase region should be more prone to cracking since they are subjected to higher resulting stress gradients for a given expansion. This would imply less cracking for low-carbon steels, which have a wider two-phase region, and no cracking for bainitic steels, which experience no phase transformation expansion. Cracking would also be expected to occur in the center of the panels where stresses are the highest.

These stress generation mechanisms explain the improved results of slower cooling rates by the lowering of internal temperature gradients and the resultant decrease in maximum stress levels. In addition, the absence of cracking in ingots smaller than two tons can be attributed to the inability of very small ingots to generate internal thermal gradients during cooling sufficient to cause stresses that result in cracking.[5]

A final factor already touched upon is the symmetry aspect in cooling. Asymmetrical cooling might set up higher, more unfavorable stresses,[5,6] but this idea needs to be developed further.

Off-Corner Panel Cracks

The stress generation also can be applied to explain the influence of thermal treatment on off-corner panel cracking.[9] As cooling progresses after the ingot has been stripped, the surface transforms to ferrite first. The transformation front then extends inward to a certain depth. However, reheating in the soaking pit retransforms the surface back to austenite. The result is a thin zone of two-phase material undergoing expansion while transforming from austenite to ferrite which is surrounded by austenite on each side. As this thin zone retransforms to austenite as well, its contraction generates a large tensile stress beneath the surface and a compressive stress on the surface. Subsurface cracks then form along the path of least resistance - the precipitate-weakened grain boundaries. The position of the cracks should correspond to the maximum depth of the original austenite-ferrite transformation front. It should be noted that the brittle, columnar, grain boundaries are in the most vulnerable orientation, being perpendicular to any applied tensile stress. Subsequently, the compressive stress on the surface causes it to deform plastically by shrinking. As the interior continues to reheat, temperature gradients subside, causing the subsurface to expand. The resulting tensile stress at the surface causes the previously formed subsurface cracks to propagate through to the surface, again along the weakest grain boundary path.

This mechanism offers an alternate explanation for why the occurrence of off-corner panel cracking is most likely when the surface falls into the two-phase region before reheating. It also predicts that cracking occurs during reheating and that a rapid soaking pit reheating practice would be the most detrimental under these circumstances.

Two additional factors have been suggested to contribute to stress generation in the cooling ingot. Firstly, the delta ferrite-austenite phase transformation occurring at high temperature in low-carbon steels is accompanied by a contraction which may generate residual stresses. Secondly, residual stresses are the highest when steep thermal gradients are present. Kawawa[11] determined that the thermal gradients in a cooling ingot reach a maximum 9000 seconds (or 2.5 hours) after stripping and correlated them with stress generation.

PROPOSED SOLUTIONS

In an effort to eliminate panel cracking, various companies have proposed and attempted a number of different solutions, meeting with varied success. Since only a small percentage of steel production suffers from panel cracks (about 1 percent), the first natural solution is to simply remove the cracks from affected ingots by grinding or scarfing them afterwards. Unfortunately, this has proven unsuccessful. Grinding is expensive and the lower, "closed" portion of the crack still opens up during rolling. Scarfing with an oxy-acetylene torch itself opens up the cracks and forces them deeper. Finally, the detection of all remnants of cracks in an affected ingot or slab is virtually impossible and the consequences of allowing a panel-cracked product to go into service could be disastrous.[5] Thus, ingots affected by panel cracks are almost universally rejected and scrapped.[12,14]

Another solution that has been suggested to reduce panel cracking is to make smaller or thinner ingots that generate smaller thermal gradients and less resulting stress,[5] but this has not been substantiated with any experimental evidence. As previously mentioned, higher ingot-to-slab reduction ratios may reduce cracks by closing them up during rolling, only if they have not yet reached the surface.

The remaining solutions to panel cracking fall into two categories: changing steel composition to improve hot ductility and altering thermal treatment to either improve hot ductility or reduce stress generation.

Steel Composition

Following the solutions to the nitride embrittlement problem previously discussed, the first composition solution to panel cracking is to lower the nitrogen content of the steel. Unfortunately, this often proves to be difficult. Nitrogen enters steel mainly by absorption and entrainment from the atmosphere so its content can be lowered, along with oxygen, by limiting exposure to air. Specifically, rough spraying streams should be avoided and well designed shroud and nozzle systems should be used.[18] Slag type is also important as acid slags result in more N than basic slags and double slag systems result in more N than single ones.[5] One company found that blowing with high purity oxygen ($>$ 99.4 percent) reduced the incidence of panel cracking.[12] It is also important to watch indirect influences on N content such as the alloying agents and deoxidizers used.[5] For example, N absorption from the air is greater for desulfurized steel.[18] Finally, furnace type is very important as N content continuously increases in going from OH to BOF to electric furnace.[5]

The second solution to improve ductility is simply to lower the Al content[5,7,9,12] and, in micro-alloy steels, the Nb and B contents as well. However, the beneficial grain refinement and recrystallization retarding effects of the nitride precipitates, so desirable in later processing stages, also are reduced. The same mechanism of grain boundary pinning, by which these processes operate, is responsible for reducing hot ductility as well. Thus, in the words of Biggs,[1] "it is very much a compromise between obtaining effective grain size control and the avoidance of panel cracking." Several studies recommend the solution of lowered Al content only if lower notch toughness values are acceptable.[5,12]

Lowering Al content is a difficult task in itself since it also acts as a deoxidizer. Several companies compromise by aiming for a composition window of 0.01 - 0.02 percent Al.[8] However, because of the extremely variable recovery of Al, this can be difficult to achieve. Adding Al directly to the ladle is one way to make recoveries more consistent. In addition, factors which control oxygen level indirectly influence ASA so should be carefully controlled. These include air entrainment, Si and Mn additions and slag type. Alternatively, Si can be used as a deoxidizer although one company finds off-corner panel cracks only in Si-killed, Al grain-refined steels.[14] Moreover, the lack of any definite trend with increasing Al content found by many studies of off-corner panel cracks makes this second proposed solution very dubious.

The third composition-based solution is the use of other, less detrimental nitride formers. Various companies have claimed success in reducing the incidence of panel cracks through the addition of Ti,[5,7,10,12] V,[5,8,12] Zr,[5,10] Mo,[5,10] or even Nb.[12] However, aluminum is generally considered to be the least critical grain growth inhibitor with respect to the introduction of undesirable non-metallic inclusions. Titanium produces undesirable carbo-nitrides, resulting in increased non-metallics and reduced machinability.[5] Zirconium is a strong deoxidizer which results in lower recoveries and increased non-metallics. Besides being very expensive, it is also less effective than Ti and again reduces machinability and notch toughness. Finally, the beneficial effects of V and Nb are in dispute, at least for off-corner panel cracking.[9,10,14]

Thermal Treatment

Although thermal treatment is highly influential on panel cracking, there is little agreement on the optimal thermal treatment. This is due, in part, to the dual role it plays in influencing both high temperature ductility and stress generation.

Mid-Face Panel Cracks

As previously discussed, the incidence of mid-face panel cracking has been reduced in many steel plants by avoiding very long track times.[5-8] Nashiwa[6] suggests that ingots be charged into the soaking pit before a maximum of 32,000-40,000 seconds (9-11 hours), depending on the jacketed time, as shown in Figure 9. Other studies are vague as to the actual limits to set but the intent is to keep the ingot surface above some critical temperature.[3,8]

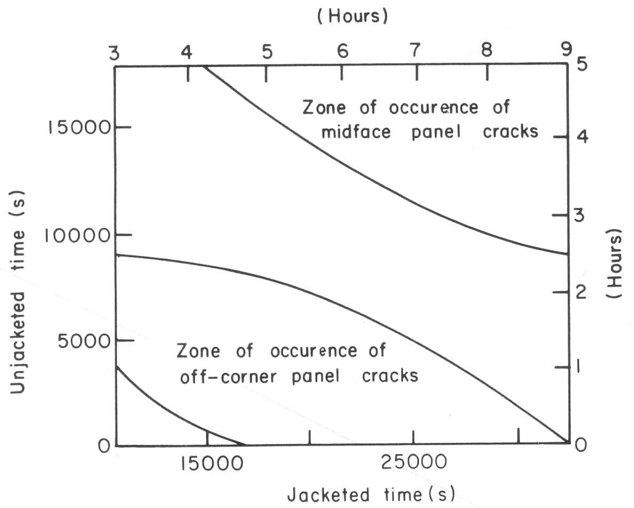

FIG. 9. Effect of cooling practice on panel cracking.[6,14]

Another solution to mid-face panel cracking is slow cooling[3,5,8] by either stacking ingots together or keeping them in a holding furnace. Cracking may increase if ingots cool while standing too close together[5,6] so symmetrical cooling may be the important feature here.

Finally, as previously mentioned, Guerin and Roccatagliata[5] found that laying one face of the hot ingot on an insulating bed of vermiculite eliminated mid-face panel cracking. This was believed due to the asymmetrical cooling allowing the one hot face to absorb all of the generated stress by plastic creep deformation.

Off-Corner Panel Cracks

A variety of different thermal solutions have met with some success in reducing off-corner panel cracking. A typical example of the cooling practices to avoid is given in Figure 9. Unfortunately, the exact times and reheating necessary are disputed, and vary between operations, as previously discussed. However, these solutions do fall into two general categories. The first is to prevent the surface from falling below the Ar_3 temperature into the two-phase region.[8,9] This is achieved by stripping the ingot early (short jacketed time) and quickly transferring the ingot to the soaking pit (short unjacketed time). Sussman[9] suggests this should be

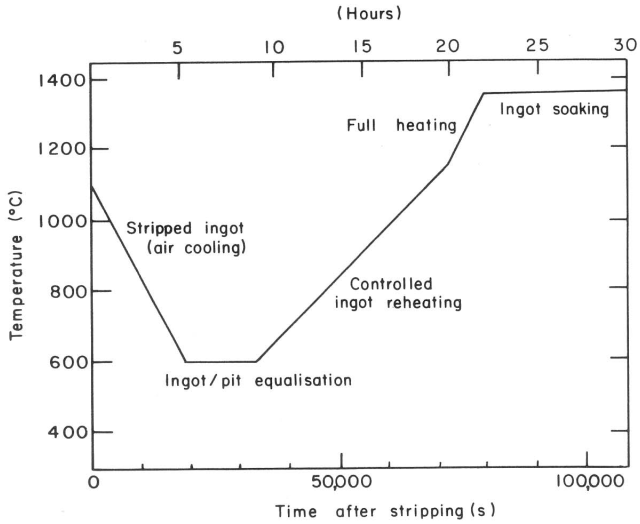

FIG. 10. Soaking pit reheating practice recommended to reduce off-corner panel cracking.[10]

followed by a rapid reheat with a high gas firing rate in a hot soaking pit. This solution has the added advantage of thermal efficiency but is often difficult to achieve due to logistics problems.[9,14] The second solution is to ensure that if the surface does drop below the Ar_3, it cools completely below the Ar_1 before reheating. This is achieved by stripping late and cooling extensively before charging to the soaking pit.[6,8-10,12,14] This solution has the disadvantage of being expensive to implement due to lower production rates, logistic problems and higher fuel consumption.[9,12,14]

Finally, several companies have found success with controlled reheating rates in the soaking pit[9-12,14] such as shown in Figure 10. Many companies achieve this by lowering the soaking pit temperature at charge for those steel compositions designated as susceptible to off-corner panel cracking,[8,10,14] and/or by increasing the time in the soaking pit.[11] Sussman[9] states that the slow cooling practice solution should be combined with slow reheating rates.

SUMMARY

Panel cracking is manifested as two distinctly different types of crack problems: mid-face cracks and off-corner cracks. Mid-face panel cracks run longitudinal down the center of one of the faces of small, medium-carbon steel ingots and arise during air cooling. These intergranular cracks propagate along proeutectoid ferrite networks found at the prior austenite grain boundaries surrounded by a hard pearlite matrix. They are alleviated by preventing the surface from cooling excessively or by slow or unsymmetrical cooling through a critical temperature range.

Off-corner panel cracks are found near the edges of the wide face of large, low-carbon, manganese steel ingots and are more associated with reheating. They have been avoided by employing either short air cooling times followed by rapid reheating or long air cooling followed by slow, controlled heating. Soaking pit conditions appear to be very influential.

Both problems are caused, in part, by a loss in the low- and intermediate-temperature ductility of steel associated with embrittlement by AlN precipitates. In addition, they are both influenced by the variations in thermal and phase transformation stress that arise during thermal processing. However, the mechanisms by which they form are quite different and the relative importance of these factors is not completely understood.

One solution to panel cracking is to cast less susceptible steel grades. The effects of steel composition on both hot ductility and panel crack formation have been documented

and are fairly well understood. The incidence of panel cracks should be reduced by employing lower nitrogen and aluminum contents, or by substituting other nitride formers such as titanium. However, these solutions are often difficult to achieve and can produce undesirable side effects.

Thus, many steel companies have adopted elaborate and expensive cooling and heating practices in an attempt to reduce panel cracking. Due to the inconclusive feedback from a complex steel plant, and the intermittent nature of panel cracking, it is not known, in the majority of cases, how beneficial these practices are. There is, therefore, a great incentive to understand the influence of thermal treatment on panel cracking.

Part I of this paper on hot ductility revealed that the effects of thermal treatment on the ductility of steel are not well understood. When combined with the generation of thermal stress and the influences of phase transformation and creep, the effects of thermal history on panel cracking are extremely complex. Most of the results from previous studies on panel cracking can be explained by either reduced ductility or stress generation, although both mechanisms undoubtedly contribute to some extent. Since the stress-related mechanisms for panel crack formation have received less attention, and are consequently the most vaguely formulated, they present a promising area for research using mathematical modeling techniques.

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