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SOME ASPECTS OF THE CONTINUOUS CASTING OF CAST IRON

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SOME ASPECTS OF THE CONTINUOUS CASTING OF CAST IRON

by

R. Thomson*

SUMMARY

The horizontal continuous casting of ductile iron is described in detail to provide a background against which the optimisation of product quality may be discussed. In this preliminary investigation, the causes of surface flaws in the casting are analysed, and a mechanism for their generation formulated.

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1. Introduction

During a commercial development of a production technique to continuously cast round bar in ductile iron grades in Canada, this Division was asked to provide some assistance in the analysis and solution of various problems concerning the surface and internal quality of the product. This report documents the subsequent technical discussions, and presents an interim account of the investigations conducted during the period August 1972 to August 1973.

To obtain a perspective against which current endeavours may be viewed, it will be useful to dwell briefly on the technical and commercial background of the interest in continuously cast ductile iron. A survey of the market for semi-finished shapes in grey and ductile cast iron suggested that ductile iron produced by continuous casting might be marketed within the price structure of grey iron products, thus yielding a sales advantage in terms of the superior properties of ductile grades. The exploration of this concept involved the twin exercises of placing the conversion of pig to ductile iron on a sound technical and economic operating basis, and simultaneously developing a market for the product. To these ends, a horizontal continuous casting machine was purchased, commissioned and subsequently employed for the technical development of the process, and as a production unit to feed the developing market for ductile iron bar. It was anticipated that a probationary period of two years would provide an indication as to the desirability of expansion of the project in the form of a multi-casting machine operation with a capability of ~15,000 tons per annum. At the end of this trial period, it was apparent that, while the marketing development had been progressing satisfactorily, improvements in the technical control of product quality and yield were increasingly hard-won, and indeed it was considered doubtful that any expansion could be shown to be economically viable using the measures of product yield available at that time. The probationary period was consequently extended to permit further technical investigations, some of which are described below.

2. Pilot Plant Equipment and Practice

Pig iron is melted and brought to composition in a 6 ton tilting induction furnace, then transferred in nominally 2 ton capacity lip-poured ladles to the 2 ton capacity holding furnace or tundish on the casting machine. The entire tundish assembly complete with water jacketed graphite moulds bolted to the side opposite the pouring lip, is cradled in stanchions in such a way that it may be tilted away from the casting machine in the event of a liquid metal breakout at the mould exit (Figure 5). Starter bars are supported by six fixed free-running roller stands in the 30 ft gap between the mould and the withdrawal stand. The latter has four driven roll shafts arranged so that up to four strands can be operated simultaneously. Four free-running hydraulically pressurised rolls bear down on the casting to maintain gripping action. A travelling cut-off saw is used to notch the castings, and is followed, in line, by a hydraulically operated cantilever loading unit to effect bar fracture at the notch.

The instrumentation and control associated with the operation is limited to immersion temperature measurements prior to tapping the induction furnace and in the transfer ladle before teeming into the heated tundish; surface temperature measurement of the casting by two indicating optical pyrometers mounted on a gantry behind the mould; and the standard controls of a Technica-Guss casting machine. These comprise four sets of 'on' and 'off' clock-type timers to define the cycle of intermittent withdrawal within the range 0 to 4 sec approximately for the duration of the stroke produced by the fixed speed roll drive motors (yielding surface speeds of 200 to 250 in. min^{-1} on V profile drive rolls) and 0 to 120 sec for the 'off' or dwell part of the cycle. Four sets of mould water controls allow adjustment of an indicated flow rate of 0 to 15 gpm to suit a specified value of indicated exit water temperature (0 to 80°C).

The casting machine is used to produce 1 to 16 in. diameter bar, with up to four strands operating for <3 1/2 in. diameter bar, 2 strands at <7 1/2 in. diameter, and single strand production at larger sizes. In a typical production run, cold pig is charged to the induction furnace. (Greater throughputs have recently been achieved on large bar sizes by charging two and three 6 ton lots of hot metal directly into the induction unit.) While the heat is being prepared, the transfer ladle is gas-heated, and the tundish assembly is installed and pre-heated by a lid-mounted oil burner. The starter bars, in practice steel pipes to which are attached solid steel dummy blocks, are held on the withdrawal stand and support rollers, and only inserted and sealed into the mould or moulds just prior to filling the tundish with the first ladle. Pre-heat times for the ladle and tundish are of the order of 3 hours. Nodularisation treatment comprises the introduction of magnesium and cerium-bearing ferro-silicon into the bottom of the transfer ladle prior to tapping the induction furnace. The additions are covered with steel scrap to slow-up assimilation in the iron. The magnesium-bearing addition varies from 36 lb per ton to 50 lb per ton depending on the sulphur content of the iron prior to treatment (0.005 to 0.030% S). The cerium addition is made at the rate of 5 lb per ton for the first and last ladles of the heat and 3 lb per ton for the remainder. Nominal starting and final iron compositions are shown in Table 1 and metal treatment rates given in Table 2.

The transfer ladle is de-slagged in front of the casting machine, using a wooden rabble held to achieve the required pouring temperature then tilt-poured at the rate of approximately 4 tons per min into the tundish. Fe-Si inoculant is continuously added to the pouring stream at the rate of 12.75 lb contained Si per ton. The specified pouring temperatures are shown as a function of bar size in Figure 1. During teeming the first ladle, an operator is stationed on the pyrometer gantry to hold back surface slag in the ladle. This practice is neglected for subsequent ladles. The delay time between the introduction of metal into the tundish and mould and the first withdrawal stroke varies from 25 sec to 150 sec over the bar size range 2 to 16 in.

The stroke length is gradually increased over the first ten cycles to that specified for the run. Since the roll drive motors operate at a fixed speed, changes in stroke length are achieved by increasing the duration of the stroke action by adjusting the 'on' timer from its minimum, equivalent to a stroke of ~0.5 in., to a setting of 0.3 to 0.6 sec to produce the required stroke. Prior to this study, the stroke length was held at 2 in., independent of bar size. During the start-up of large bars (>6 in.) hand-held water hoses are used to chill the starter block and the first few inches of casting as it appears at the mould exit. The purpose of this is to decrease the temperature of the keyed area of the casting and reduce the possibility of hot tensile fracture of the keying bolt.

The net casting speed attainable per strand varies with bar size as shown in Figure 2. Since the stroke length is fixed for a given cast, it follows that adjustments to casting speed are made by varying the dwell period per cycle, typical values being given in Table 3. Operator adjustments to dwell time are controlled in turn by the indicated temperature of the bar surface, i.e., if the temperature increases above a specified value, the dwell period will be increased by a few seconds for subsequent cycles, and vice versa. Optimum bar exit temperatures are given in Figure 3. It should be noted that the maximum bar surface temperature occurs several inches from the mould exit, so that the pyrometers have to be sighted in for each combination of bar size and stroke length. Mould water flow rate is adjusted to maintain an indicated exit temperature of 60°C. In practice, the flow rate per strand ranges from 5 to 10 gpm.

TABLE 1

Typical pig iron and ductile iron compositions (wt per cent)

	C	Si	S	Mg	Sn	Ti
Pig iron	3.6	0.22	0.01	--	--	.03
Ductile iron	3.4	3.0	0.008	>0.04	0.01/0.05	.03

TABLE 2

Nodularisation and inoculation treatment (lb per ton)

	Low S pig	High S pig	Avge.
9% Mg FeSi	36	50	40
2% CeFeSi	--	--	4
85% FeSi inoculant	--	--	15

TABLE 3

Nominal dwell times vs. bar diameter for 2 in. stroke length

Diameter (in.)	2	4	6	8	10	12	14	16
Dwell time (sec)	3	6	10	14	18	24	24	26
Casting speed (in.min^{-1})	40	20	12	10	7.5	6	5.5	5.0

The tundish lid burner is kept on during casting, and is only shut down when new ladles of metal are teemed. This occurs when the level of liquid in the tundish approaches within 4 to 5 inches of the top of the mould. While the second and subsequent ladles are being emptied, casting withdrawal is continued normally, although close attention has to be paid to bar surface temperature.

Departures from normal operation may be occasioned by incipient melting of the casting skin outside the mould; seizure of the casting in the mould caused by a cracked mould; service failures to the plant, e.g., power failure to the withdrawal motors. The first of these situations may be dealt with in one of two ways. First, prompt use of a water hose applied to a hot spot, usually at the top of the casting, may prevent liquid metal break-out. Failing such early detection of a break-out situation, a run out of liquid metal can be arrested by reversing the roll drive so that the part of the surface which has re-melted is again contained by the mould. After an appropriate dwell time, extraction can then continue with the judicious use of the water hoses on the healed break-out zone of the bar surface.

Quality control is exercised by obtaining a sample slice from the last bar length cast from each ladle during the run. This is assessed for hardness (across a diameter), tensile properties, porosity, inverse chilling, and degree of nodularity, the latter three being determined by metallographic examination. Based on these tests, accepted bars are machined to size and finally inspected for sub-surface defects revealed by machining. Rejected bar at this stage may be re-cycled, or re-machined to the next lowest specified diameter.

3. Problem Areas

Four separately identifiable phenomena were reported to be major contributors to the reject rate of cast bar. These were:

a) Surface flaws below which the metal was cracked sometimes to a depth of 0.75 in., so that surface cracks were in evidence after machining the bar to its specified diameter. In most instances re-machining to the next lower size specification removed the defect, but this step is, of course, prohibitively costly. This defect type is dealt with in Sections 6.1 and 6.2 below.

b) Hard spots on or just below the bar surface are revealed on machining as the tool bit is severely damaged on contact and ceases to cut properly. In general such a defect results in the automatic rejection of that bar length. The defect was tentatively identified with slag inclusions in the cast bar, their possible sources being ladle or tundish slag, ladle or tundish refractory lining, or partially oxidised FeSi inoculant.

c) Inverse chilling in the centre area of the bar, i.e., solidification to white iron in the last areas to freeze. As the size of the liquid core of the casting diminishes with time, the heat extraction rate from it increases and the efficacy of the initial inoculation treatment fades, both factors increasing the potential for undercooling to occur to the extent of local nucleation of eutectic solidification of austenite-carbide. Where metallographic examination of central areas of the bar reveals more than 3 per cent by volume of carbide phase, that bar, and probably subsequent bar lengths from that ladle, are rejected.

d) Magnesium fade refers to the loss of that element from the liquid with time, and the consequent deleterious effect on graphite nodule shape in the iron. This results in a rejection rate of bar lengths for reasons of unacceptable nodularity which tends to become more severe as the liquid contents of the tundish are used up, i.e., prior to each tundish re-fill. The problem is more generally one concerned with magnesium loss from the time of treatment to the time of solidification.

A survey of the incidence of various defects occurring over a six month production period revealed that rejection rates for surface flaws and inclusions varied roughly between 10 and 50%, and were highest for the middle sizes of the product range, i.e., 4 to 10 in. diameter. These data, illustrated in Figure 4, and summarised in Table 4, only serve to indicate a trend however, and should not be used as a statistical measure with which to compare later results, for the following reasons. Firstly, the sample size varies between bar diameters with an insufficiency of data at larger diameters; and secondly one defect may have appeared twice as a result of re-machining, or conversely a bar originally noted as defective after one machining operation may have contributed to the acceptable bar population after subsequent reduction in diameter. Despite these restrictions in interpretation, the data clearly illustrate the extent of the problem of surface quality control.

While no similar analysis was conducted on the incidence of inverse chilling and lack of adequate nodularity, quality control data obtained on a monthly basis indicated that these problems were much less severe and contributed a tolerable 3 to 8% to the rejection rate. Accordingly, the priorities of investigation were set in the order (a) to (d) shown above.

4. Previous Development Work

It being apparent at the outset that the surface and sub-surface defects described above were more likely to be related to the continuous casting conditions and practices employed, rather than, for example, to some specific thermo-mechanical or thermo-chemical property of ductile iron, it will be of some value to examine some of the casting variations explored in the two years of development work preceding this study.

The most significant modification of the original Technica-Guss design has been the incorporation of a baffle plate in front of the entrance to the mould cavity. A sketch of the tundish-cooler assembly is given in Figure 5, with the baffle plate shown in dotted lines in area A. Prior to this innovation, the cast bar exhibited major surface defects, such as unhealed cracks at lap marks, surface flaws, and cold shuts, predominantly between the 4 and 8 o'clock positions on the bar perimeter (Figure 6). Relating these effects to the presence of a fairly static body of colder metal at the bottom of the tundish, it was proposed that the use of a baffle would effectively scour this area with hotter metal every extraction cycle, and so raise the mould surface temperature in that perimeter under the baffle, thus eliminating "cold metal" casting defects. In fact, the baffling of the upper 2/3 rds of the mould cavity area did not entirely eliminate the defects, but instead altered their predominant location on the bar perimeter to the 8 o'clock through 12 to 4 o'clock arc, as indicated in Figure 6. The small hole in the baffle plate below to the 12 o'clock position was drilled to vent the mould cavity during start-up. Its size was subsequently increased from 1/4-in. diameter to approximately 3/4-in. diameter with the object of providing an escape path for entrapped slag floating to the top of the mould cavity. Another important function of the baffle is in limiting the incidence of break-outs on the upper surface of the bar by preventing the temperature gradient in the tundish being directly imposed on the mould cavity.

A technique was developed for continuously measuring the temperature of liquid entering the mould in order to more closely relate ladle pouring temperatures with actual casting temperatures. A channel was drilled in the tundish housing to allow the insertion of a silica sheathed thermocouple into the liquid in the bottom of the tundish. This is represented by a dashed line in Figure 5. Although some washing and deformation of the sheath took place, some useful results were obtained confirming the function of the baffle plate in that the liquid temperature at the tundish bottom was seen to oscillate 15 to 20°C in phase with the extraction cycle. One unresolved problem with this monitoring system was the inexplicably low temperature values recorded in relation to the known ladle pouring temperatures.

The shape of the tundish and the use of the lid-mounted burner combine to induce a significant temperature gradient down through the liquid. Acknowledgement of this undesirable characteristic has been made by the machine manufacturers in making available an induction stirring device which is attached to the outside of the holding furnace at area B in Figure 5. In the absence of this device, some attempts were made to use argon stirring in the tundish. It is not known whether this test was successful in evening out liquid temperatures.

With respect to surface flaws, the problem was correctly diagnosed as being the result of a mechanism occurring in the zone of the mould in which initial solidification of the shell takes place. This zone will be subsequently referred to as the upper part of the mould, i.e., up meaning in the direction of the tundish. It was assumed, again correctly, that increasing the mould wall temperature in this area might restrict the build-up of successive solidified layers and thus either eliminate flaws, or at least decrease their severity to a level that could be handled in the machining operation. To this end, at least two changes in mould design were investigated. In the first, a notch was cut in the outside wall of the graphite mould with the object of restricting heat flow from the nozzle section projecting into the tundish to the lower part of the mould surrounded by the water-jacket. In the second test, the length of the graphite mould was increased by 1.5 in. so that the upper part of the mould protruded further into the tundish. In the absence of a baffle plate, this would almost certainly have increased the upper mould wall temperatures. However, the method of cementing the baffle to the tundish wall effectively insulated the extended nozzle, and the trial became inconclusive from this point of view. Neither test, in fact, served any useful purpose because, unless flaws had disappeared completely, there was no established method of using flaw incidence to detect any effect of mould design changes. The subject of water-jacket/graphite mould design is worthy of further consideration.

The effect of stroke length on flaw incidence was investigated in a cursory fashion, much hope again being placed on the disappearance of the defects. For a number of production runs, the commonly used stroke of 2 in. was increased to 4 in., but lack of control data on flaw incidence before and after this change rendered interpretation of its effect highly speculative.

Finally, it was proposed that the roll speed may be a contributory factor in flaw generation, it being held that lower extraction rates would result in a smoother removal of the cast shell, and the lower strain rates would incur reduced surface cracking. This theory could not be economically investigated due to the problem of gearing down the roll drive motors. However, it should be feasible to fabricate two sets of rolls with a ratio of diameters of 2:1 and, with proper flaw monitoring, evaluate the influence of effective roll speed. In general, in closed systems it is more probable that increasing roll speed will improve surface quality than vice versa.

5. Proposed Investigations and Specific Recommendations

The balance of this account falls into two parts, the first of which encompasses the detail of casting plant trials and analytical work performed in Ottawa and fully described in Section 6 below. The second part is more difficult to present since it is an attempt to document the dialogue concerned with the initial approach to problem solving, and subsequent correspondence dealing with the implementation of the points raised. For convenience these items are presented in chronological order in Appendices 1 to 6 and describe the general line of attack to be used against surface quality problems and the necessary changes in casting procedure (Appendix 1); the rebuttal to these suggestions and an experimental programme based on them (Appendix 2); further comment on casting trials and recommendations for sampling continuously cast bar (Appendix 3); general comment on the part played by mould lubricants in continuous casting, and their non-applicability to horizontal closed-head units of the present type (Appendix 4); a broader programme proposal to relate surface flaws to casting parameters (Appendix 5) and comment on this (Appendix 6).

It is pertinent to briefly examine these appendices with a view to bringing their contents up to date. Of the initial proposed steps to reduce or eliminate surface cracking (Appendix 1) the metallographic analysis has been completed and is described in Section 6.2 below. Similarly, the examination of the superheat of the tundish contents has been completed and is described in Section 6.1. The suggestions that baffle design and stroke length be varied to determine their effect on flaw incidence were neatly incorporated in the experimental programme outlined in Appendix 2, and casting trials were in fact carried out on small and medium sized bars. Unfortunately these trials were suspended due to the necessity of fulfilling production requirements and the data obtained, though submitted to statistical analysis, proved to be insufficient to yield any irrefutable conclusion. It was evident, however, that there appeared to be a lower incidence of flaws using combinations of smaller baffle openings and longer stroke lengths, and in fact these conclusions were adopted and casting practice altered accordingly. Thus, since these initial trials the baffle has been installed so as to cover 80% of the mould area, and the stroke length has been increased to 4 in. for normal production runs. A second attempt to analyse the effect of casting parameters on flaw incidence was proposed (Appendices 5 and 6), but has not been initiated at this date. Likewise, no experiments on the effect of mould surface characteristics have been conducted.

Of the second group of general suggestions given in Appendix 1, and concerned solely with the problem of hard spots or slag inclusions, the only recommendation adopted was that the tundish be refilled during an extraction dwell period. It is not known to what extent this simple change in practice may have reduced the rejection rate due to hard spots, but it appeared to be eminently desirable from the point of view of operator control of the casting operation. Prior to this change, the addition of a new ladle of metal to the tundish produced large fluctuations in bar exit temperature, and as will be discussed below, gave rise to increased density of hard spots and surface flaws on bars cast during tundish re-fill. In fact it became standard practice to reject the last bar length cast before a new ladle, and the first bar length cast during re-fill, before machining. These excursions from between-ladle operating conditions were caused by the introduction, into the mould and liquid sump, of hot metal directly from the ladle when an extraction stroke was made during teeming.

Proceeding to the specific changes recommended in Appendix 1, and commented on in Appendix 2, items 1 to 4, 8, 9, 10 have not been implemented. Of the remainder both Tec-tip analyses prior to inoculation, and a design of tundish pyrometer, have been tried. These were intended to yield data on the actual superheat of the liquid entering the mould cavity. A flaw detection station was in fact organised for those trials varying baffle opening and stroke length. This involved a technician noting the placement of flaws on the bar as it left the mould, i.e., assembling the raw data on flaw incidence. This was a particularly arduous and difficult task since it involved close concentration in an uncomfortable environment. It may be more reasonable in future to count only those flaws of economic importance, i.e., those remaining after machining.

6. Experimental Investigations

6.1 Liquid Superheat and Tundish Temperature

As part of the general approach to the flaw problem it had been suggested that higher degrees of superheat of the metal entering the mould may reduce the incidence of flaws. To explore this possibility, and to simultaneously increase knowledge of the temperature distribution in the tundish, a production run was made in which the ladle pouring temperatures were varied, and a temperature exploration of the tundish was carried out throughout the cast using immersion thermocouples. The normal ladle teeming temperature for the 5.3-in. diameter bar produced is 1310°C (2390°F).

The experiment was designed to pour the first ladle at the normal production temperature of 1310°C and succeeding ladles at 1330, 1350 and 1370°C respectively. Immersion temperature measurements were taken approximately 4 in. from the tundish bottom just after a ladle re-fill, again when the tundish was half-full, and finally just prior to re-fill. At several times during the cast, additional temperature measurements were obtained just below the liquid surface and approximately halfway between the surface and tundish bottom. The results are given in Table 5 and Figure 7. The freezing range of the iron estimated from its carbon equivalent, was liquidus 1136°C (2075°F) and solidus 1127°C (2062°F). Ladle No. 1, poured at the normal temperature for the 5.3-in. diameter bar, gave a liquid temperature near the mould entrance of 1230°C (2246°F) at the start of the cast, falling to 1215°C (2219°F) prior to the addition of ladle No. 2. Having a higher degree of superheat, ladle No. 2 raised the liquid temperature at the tundish bottom. This had immediate repercussions with respect to casting speed control, because the bar exit temperature increased to 1090°C (1996°F) and had to be subsequently brought back to 1060°C (1940°F) by using longer dwell times thus reducing the net casting rate. Indeed at one point water jets were used on the top surface of the bar to reduce the risk of break-out. It was stated that for this size of bar, experience had shown that a run-out would occur if the surface temperature exceeded 1126°C (2060°F) with the tundish more than half-full. Under these forced conditions of slower casting rate compared with ladle No. 1, the liquid was held in the tundish for a longer time, during which the initial superheat was slowly dissipated, and both the bottom temperature and the casting rate returned to the values observed for ladle No. 1. The same sequence of events was observed for ladle No. 3 poured at 1349°C (2460°F). The casting rate had to be reduced, only to return to the normal level when the liquid had cooled to 1220°C (2228°F) at the mould entrance. In view of this behaviour, ladle No. 4 was teemed close to the normal temperature and the experiment terminated.

Two separate estimations of the vertical temperature gradient in the tundish contents are illustrated in Figure 7. Two factors affect the accuracy of this assessment. It was difficult to gauge the depth of immersion of the thermocouple, so that the ordinates of each point are only accurate to ±2 in. Secondly the paper-wound expendable thermocouples produce vigorous boiling upon immersion, so that some stirring action and consequent lowering of temperature gradients occurred. In fact, prolonged immersion produced so much bath agitation that the effects could readily be observed in increased bar surface temperatures at the mould exit.

The conclusions that may be drawn from these tests are:-

a) It is not possible to unilaterally increase the degree of superheat of liquid entering the mould cavity, since such a step must always be accompanied by a decrease in casting rate.

TABLE 4

Defect Incidence on Cast Bars

Size range - 2 to 15 in. diameter
No. bars examined - 404

Defect	No. bars with defect	%
Surface flaws	114	28.2
Sub-surface inclusions	118	29.4

TABLE 5

Observed Tundish Temperatures*

Ladle No.	Teeming Temperature		Tundish Temperature					
			A		B		C	
	°C	(°F)	°C	(°F)	°C	(°F)	°C	(°F)
1	1300	(2372)	1230	(2246)	--	--	1215	(2219)
2	1338	(2440)	1260	(2300	1220	(2228)	1200	(2192)
3	1349	(2460)	1240	(2264)	1240	(2264)	1220	(2228)
4	1325	(2414)	1225	(2237)	1220	(2228)	--	--

* - Probe held 4 in. from tundish bottom.

A - One minute after ladle addition.

B - Tundish half-full.

C - Immediately before a new ladle addition.

b) There is a vertical temperature gradient in a full tundish of the order of 100C° (180F°) from the liquid surface to the bottom of the tundish.

c) Under normal conditions of casting 5.3-in. diameter bar, the liquid enters the mould cavity at 1210 to 1230°C (2210 to 2246°F).

d) Tundish temperature measurements should be made using a refractory thermocouple assembly, e.g., SiC.

Conclusion (a) only holds true provided the mould/cooler design remains constant. If, however, the effective mould length was increased by 50 to 100% then it would be possible to maintain the presently used casting rates and so examine the single effect of superheat on flaw incidence.

6.2 Investigation of Surface Flaws

As indicated in Appendix 1, a metallographic study of surface flaws was undertaken in Ottawa with a view to formulating a theory to account for their generation, and, by extending the argument, to infer and possibly test casting conditions which might be expected to reduce their incidence. Initially, samples of flaws were obtained more or less randomly from normal quality control sampling procedures. After the significance of sampling technique was analysed (Appendix 3), defect samples were selected during the casting operation by marking for removal from the bar sample logs which were long enough to include two stroke lengths (2 in. per stroke) preceding and succeeding the defect. Approximately 15 such sample logs were examined, many of these containing more than one flaw, from bars 6 to 8 in. diameter. A total of 20 individual flaws were studied. Their characteristics will be listed in terms of observations made during the actual casting operation, visual examination of the cast surface, and finally microscopic examination of sections through flawed areas.

Flaws may be identified on the hot bar surface beyond the mould exit as dark elliptical areas having their long axes at right angles to the casting direction. The colour difference arises because the sub-surface discontinuity offers a barrier to radial heat flow, with the result that the metal above the discontinuity, i.e., closer to the surface, cools much faster and therefore appears darker than the surrounding un-flawed area. The degree of visual contrast between the flaw and the orange-red of the adjacent homogeneous material may be taken to indicate the severity of the defect. It can be argued that marked contrast, i.e., a flaw which appears black indicates a shallow discontinuity, there being only a thin web of metal to permit heat flow to the surface above the discontinuity from the surrounding hotter areas of the bar surface. Conversely, a grey appearance indicates a deeper discontinuity above which the surface can receive heat laterally from preceding sub-surface material. Generally, these grey flaws are non-uniform having a gradation black to grey in the casting direction. On the basis of the above hypothesis relating colour to depth of cracking, this gradation indicates that the discontinuities proceed from the surface into the casting in the casting direction, an observation confirmed by subsequent metallographic examination.

The relationship between flaw appearance on the hot bar and the severity of the defect is of some significance when flaw incidence is being monitored visually during a casting run, since the observer must guard against the natural impression that the blacker the surface mark the more significant the underlying defect. Clearly the reverse is true, since black shallow discontinuities will almost certainly be undercut during the production machining operation. It has been proposed that the assumed relationship between flaw colour and crack depth be confirmed by recording on film the appearance of selected flaws, and subsequently sectioning those areas for metallographic examination.

Three other characteristics of flaws may be noted during the casting operation. One has been mentioned above (Section 4), viz. the occurrence of flaws only on that segment of the bar perimeter which solidified behind the mould baffle plate (Figure 6). Secondly, the defects may appear cyclically at the same co-ordinates of the bar surface, i.e., with a repeated interval between flaws of 6 to 100 in., or 1/2 to 10 min in terms of casting time. Alternatively, such a series of flaws may be successively displaced on the bar surface (Figure 8), i.e., the co-ordinates of the flawed area shift progressively in one direction. These observations do not apply to every flaw event, but are extremely valuable in that they suggest that flaw generation is in some way rate-controlled, and may be nucleated by a previous flaw in the same, or an adjacent, area of the bar surface.

Lastly, the incidence of flaws was increased significantly during the process of adding a new ladle of metal to the tundish. Indeed, prior to the commencement of this study, that portion of the cast produced during tundish re-filling was automatically culled prior to the machining operation. It might be inferred, then, that flaw generation was in some way adversely related to the disturbance of mould cavity temperature distribution by the direct intrusion of hot ladle metal into that zone during tundish re-fill.

An examination of the flawed surface of cold cast bar produced the following observations (illustrated in the sketch in Figure 9):-

a) the leading edge of the flaw was a continuation of the normal lap mark above and below the flawed area.

b) the trailing edge was marked by the beginning of the normal cast surface containing linear surface excrescences parallel to the casting direction.

c) these 'score marks' on the surface extended from lap mark to lap mark in the stroke lengths preceding a flaw occurrence. Inside one stroke length, the marks increase in severity in the casting direction. On the same co-ordinates of the bar, but following a flaw event, the score marks disappeared 1/2 to 3/4 in. in front of the following lap mark.

d) while normal lap marks on the bar surface were fairly even and almost at right angles to the bar axis, those pre-ceding a flaw event often displayed a progressively increasing bulge convex to the casting direction on that area of the bar perimeter which subsequently yielded a flaw. The lap mark following a flaw event was normal.

e) the flaw surface itself was of a reddish hue compared with the grey or velvet black of the surrounding scaled metal, and appeared to be depressed below the adjacent cast surface.

f) it was occasionally possible to peel back the surface skin of a flaw revealing a succession of overlapping thin layers of metal underneath. These resembled surface cold shuts and are illustrated in Figure 10.

g) some flaw surfaces were seen to contain fine parallel score marks lying at angles of up to 90° to the casting direction. Where underlying layers could be examined by peeling back the upper skins, it was noted that the degree of disorientation of score marks varied from layer to layer. Since the markings were originally imprinted on the solidifying layer of metal by longitudinal scratches on the mould surface, the evidence suggests that the material comprising the surface layers of a flaw was twisted or rotated after solidification.

These observations will be referred to below in the discussion of a mechanism of flaw generation. A typical flaw is illustrated in Figure 10.

Following the procedures indicated in Appendix 3, metallographic sections taken parallel to the casting direction were prepared from adjacent samples cut to include the lap mark preceding a flaw through to that following the flaw. An example of this type of linear sampling of the sub-surface of the bar is depicted in Figure 11, the corresponding photomicrographs being shown in Figure 12(a) to (g). In these and all other illustrations the casting direction is from left to right and the cast surface is at the top of the photomicrograph.

The section through the flaw, Figure 12(d), shows a myriad of what appear to be over-lapping cracks running into the bar in the casting direction. The major crack surfaces were slightly oxidised, while some of the finer discontinuities were completely filled with graphite. Closely associated with the flaw is a zone of slightly larger graphite nodule size than is found in the immediately surrounding area. Neither the preceding nor succeeding lap-mark sections, Figure 12(a) and 12(g) respectively, revealed any evidence of sub-surface discontinuities or local variations in nodule size. Other sections in the series were free of these particular characteristics, and revealed only a gradual variation in nodule size throughout the stroke length, and in one case, Figure 12(f), a sub-surface blow hole which has produced local surface deformation.

The location of the surface lap marks are arrowed in Figure 12(a) and (g), and the leading edge of the flaw in (d).

All such linear series of samples were similar in that there were no microstructural characteristics of note either in front of, or behind, the flaw itself, so that it will be sufficient to illustrate the evaluation with reference only to examples of actual flaw sections.

The defect shown in Figure 12(d) was one of a cyclic group of three which appeared at the same position on the perimeter of the bar at intervals of 68 in., equivalent to a casting time of approximately 7 min. The other two flaw sections are shown in Figure 13 and display the same type of closely grouped discontinuities. A section of a similar flaw is illustrated in Figure 14. Here the discontinuities lie at differing shallow angles to the surface then hook inwards at a steep angle to the surface. It is also noteworthy that in the area depicted in Figure 14, the trailing crack separates a zone of large graphite nodule size from the finer graphite dispersion of the following cast metal.

The latter characteristic is repeated in the group of three flaws shown in Figures 15(a) and (b) and 16(b). In these examples, which are not cyclically related, having been drawn from different casts, both the leading and trailing discontinuities form parts of boundaries between zones of different nodule size, and the enclosed large nodule zone appears to have been pulled away from the cast surface (Figure 16(a)). Further examination of the trailing discontinuity of Figure 16(b) at higher magnification is illustrated by a traverse across the shallow, linear part of the discontinuity,(Figure 17), and the detail of the abrupt termination of the crack and the continuation of the microstructurally sound nodule transition boundary, (Figure 18). This clearly identifiable radial boundary between matrices having different nodule densities, but being otherwise coherent, was commonly observed below the root of the trailing discontinuity of a flaw. Similar nodule transition boundaries were found in two flaw-free sections taken across the lap marks preceding two separate flaws. These unique instances of nodule size change are illustrated in Figure 19(a) and (b), and show that the transition boundary is coincident with the lap mark on the bar surface. The significance of these various features with respect to ingot shell behaviour is discussed in detail below.

Approximately half of the flaws examined displayed multiple cracking of the type shown in Figures 13 to 16. The others contained a single large discontinuity originating either at the leading or trailing edge of the surface of the flaw. Two examples of the former type are given in Figure 20.

To further investigate the spatial relationship between flaws and the zones of large nodules, several flaws were sectioned perpendicular to the casting direction along a line corresponding to the major axis of their approximately elliptical shape. Parts of two of such transverse sections are shown in Figure 21. It was found that the large nodule zone was in fact restricted to material sub-tending the surface area of the flaw, and displayed the abrupt transition boundary, sometimes containing a discontinuity as in Figure 21(a), already noted in longitudinal sections. To further confirm the exclusive association of surface flaws with large nodule matrices, several sections were prepared through the normal lap mark adjacent to, i.e., above and below, the leading edges of flaws. None of these showed a sub-surface matrix containing large nodules.

Transverse sections revealed two other features of note, both of which are readily illustrated in Figure 21. First and most obvious is the planar layer structure of the discontinuities, which, when combined with the appearance of previous sections, permits the construction that the surfaces of the discontinuities resemble a series of stacked rimmed platelets tilted into the casting. The final note concerns the gradation of nodule size within the large nodule zone itself. From Figure 21(b) particularly, it is apparent that nodule size increases with depth below the surface up to the boundary separating the areas of large and small nodules.

Following metallographic examination, a survey was made of the depth of cracking and the size characteristics of large nodule zones, the results being given in Table 6. The average maximum crack depth was surprisingly small (0.054 in.), and the maximum thickness of the large nodule zone was found to be of the order of 0.11 in.

Continuing the list of observations made on cold bar (a) to (g) above, the predominant metallographic characteristics of flaws may be summarised as follows:-

h) all cracks or discontinuities run into the bar in the casting direction and originate within the surface boundaries of the flaw.

i) the discontinuities have surfaces resembling flat platelets lying at a shallow angle to the surface at first, then altering abruptly to a transverse path. The tilt angles of successive crack paths decrease from left to right in a flaw, i.e., in the casting direction.

j) the sub-surface structure of flawed areas contain larger graphite nodules than the surrounding sound metal. The large nodule zone is usually bounded by the cracks originating from the leading and/or trailing edges of the flaw surface.

k) the majority of flaw sections, and two mechanically sound lap mark sections, displayed a coherent nodule size transition boundary proceeding radially into the casting to a depth of 0.1 to 0.2 in. In all cases the large nodule area was to the right of the boundary when examined with the casting direction left to right.

TABLE 6

Measurements of flaw depths and large nodule zones (in tenths of one inch)

Sample No.	Type of Cracking	Maximum Crack Depth	n	N
1	Multi	.42	-	1.4
2	Multi	.25	.83	1.1
3	Multi	.42	1.1	1.6
4	Multi	1.0	1.6	2.0
5	Multi	.83	1.6	2.2
6	Multi	1.1	.83	1.1
7	Multi	.83	-	.67
8	Multi	.83	-	.55
9	Multi	.3	-	.3
10	Multi	.42	-	1.1
11	Multi	.83	-	-
12	Single	.42	-	.3
13	Single	.42	1.3	1.3
14	Single	.42	.83	1.4
15	Single	.52	-	1.6
16	Single	.52	1.1	1.6
17	Single	.20	-	.3
18	Single	.67	-	.83
19	Single	.52	-	.52
20	Single	.06	.83	1.0
Averages		.54	1.1	1.1

n - depth of radial wall of large nodules

N - maximum depth of large nodule zone

ℓ) while the large nodule area is normally bounded on one side by the sample surface, it appeared in some instances to have been pulled away from the surface into the body of the casting.

These listed macro- and micro-observations of the characteristics of flaws will now be employed in an attempt to construct a hypothesis describing flaw generation. The details of the argument may be omitted by referring to the summary appearing on page 45.

The best starting area is perhaps that which will identify the nature of a flaw, and so resolve which of the terms 'discontinuity' or 'crack' is accurate. Up to this point, indiscriminate use has been made of both terms in reference to the same sub-surface facet, though their proper meanings reflect quite different events and mechanisms. A discontinuity, in the present frame of reference, is a boundary created by liquid metal solidifying in contact with solid metal of the same composition, with no re-melting of the solid "mould" to establish a weldment between the freshly introduced liquid and the pre-existing solid. This, of course, is an explicit definition of the familiar "cold lap" or "cold shut" of cast surfaces. While it is hardly necessary to define a crack to such lengths, it is of significance here to note that a crack boundary separates two bodies of metal which previously solidified, or were in the process of solidifying, as a cohesive whole and therefore have similar thermal histories.

The question then is whether flaws result from cold shuts, or from stress-induced cracking or hot-tearing. The observations made in f) and g) above, together with the evidence of Figure 10, lend support to a mechanism involving cold-shuts, while the characteristics given in j) and illustrated in Figures 14 to 18 may be used to discount the possibility of the operation of hot-tearing or hot-cracking, using the following argument. The presence of large nodules reflect a relatively slow cooling rate during solidification of the eutectic, so that in those instances in which a discontinuity separates a large from a small nodule area, it can be assumed that these two zones solidified under different conditions of heat extraction, and therefore at different times, and probably locations, in the mould. From a consideration of the position of the large nodule zone, it can be argued that this area solidified before the surrounding material comprised of the normal fine nodule structure. The first conclusion then is that flaws exhibit the characteristics of cold-shuts and should be referred to as discontinuities rather than cracks propagated through solid or semi-solid metal.

The next step in the argument is to locate the area of flaw generation in the mould using the specific association of flaws with metal displaying large graphite nodules. Since nodule size is an inverse function of solidification rate, it follows that the flaws were generated in metal undergoing conditions of slow solidification and therefore low heat extraction rate, which conditions exist only in the nozzle part of the mould at the tundish end of the cooler assembly, i.e., in the area of initial solidification of the ingot shell.

Before attempting to account for the coincidence of flaws with lap marks on the bar surface, item (a) above, it will be necessary to describe the mechanism of normal, flawless, lap mark formation. There are in fact two possible idealised modes of behaviour of a freezing ingot shell subjected to intermittent withdrawal. It may move in its entirety down the mould wall so that the original linear interface between the mould, the liquid and the tip of the shell assumes a new position in the mould one stroke length below its old one; or, the frictional forces acting across the mould-billet interface in the zone of initial solidification are large enough to induce rupture stresses at some point in the ingot skin, fracture occurs, and only the lower part of the ingot shell moves one stroke length, leaving the upper ring of the shell adhering to the mould wall where it may undergo some re-melting in the newly admitted superheated liquid. These alternatives of shell behaviour are illustrated in Figure 22, to which might be added an intermediate mechanism, namely the case where fracture occurs very close to the tip of the ingot shell and the upper portion is completely re-dissolved by the incoming liquid.

There are a number of speculative considerations lending support to general acceptance of the fracture model:-

1. The frictional load imposed on the shell at the beginning of a stroke is likely to exceed the rupture strength of the hot austenitic tubular casting because of various factors which might be

expected to increase the adhesion of the shell to the mould wall. These are the ferrostatic pressure of liquid inside the ingot skin; the pre-shrinkage expansion associated with eutectic graphite precipitation; the mechanical interlocking at the mould-ingot interface before contraction of the shell occurs; and lastly some degree of chemical bonding at the high temperature austenite-graphite mould interface.

2. The peripheral wrinkle on the cast surface known as a lap mark can be accounted for by the minor intrusion of liquid metal into the mould-billet gap at the lower fracture edge on completion of a stroke. Occasionally this lap of metal is associated with a small cold shut as illustrated in Figure 22. If the fracture-free model were operative, it would be difficult to depict how lap marks and cold shuts might form at the tip of the complete ingot shell.

3. During the dwell period of intermittent extraction, the electro-magnetic braking system on the extraction unit locks the casting between the pinch rolls. When the brake is released immediately before an extraction stroke, the rolls are seen to turn approximately 1/4 in. on their periphery against the casting direction, i.e., the casting at that point moves back toward the mould. This reversal may be explained by the release of longitudinal

contraction stresses set up in the cooling bar during the dwell period. It follows then that there exists at the mould end of the casting a restriction equivalent to the braking power of the pinch rolls, viz. the frictional forces acting across the mould-billet interface.

4. Direct evidence of a fracture edge at a lap mark is shown in Figure 19, and many similar transverse nodule transition boundaries have been noted in sections of flawed areas.

Adopting the cyclic fracture hypothesis, it is significant to the development of the present argument to identify the probable position of fracture on the mould wall, since, from the relative locations of flaws and lap marks on the casting, the site of flaw generation may then be fixed. There are two schools of thought on the disposition of the ingot shell in the mould at the end of a dwell period and therefore just prior to a fracture event. The first suggests that there is no liquid in contact with the mould wall, i.e., the solid shell extends back to the graphite baffle closure at the tundish end of the mould. The fracture plane is then held to be almost coincident with the inside surface of the baffle, the restraint opposing withdrawal being produced by solid shell keying at the baffle-mould junction. The slow solidification which produces the large nodule zones takes place on, or very close to, the un-cooled baffle plate, and the radial nodule transition boundary, and occasionally noted individual radial "cracks" are believed to reflect the interface between the casting and the baffle plate. These radial discontinuities and their cause will be discussed below.

A second opinion holds that during normal operation, there is a region of mould-liquid contact in the protruding nozzle end of the mould so that the tip of the ingot shell at the end of the dwell period lies a short distance from the baffle plate. Supporting this view are previous studies of water-jacketed graphite moulds using radio-tracers which located the point of initial solidification close to the point of emergence of the mould from the water-jacket; and the more significant evidence offered by the appearance of a typical mould surface at the end of a cast. In the composite illustration of Figure 23 is shown a section of the inside surface (side-wall) of a used mould of approximately 7-in. internal diameter and its position in the water jacket. Four characteristic areas can be identified along the mould length. AB, where A abuts the baffle plate, is smooth and retains the imprint of machining from mould manufacture. A thin band at B is characterised by the presence of small flat particles of metal embedded in the graphite. This is followed by a zone about 1/2 in. in length, BC, of relatively smooth graphite containing occasional fine longitudinal scratches. The majority of scratches, or score marks, on the mould surface originate at a poorly defined boundary, C, and become more numerous and deeper over the remainder of the mould length, CD. These differences in mould surface characteristics produce an equivalent imprint on the cast bar surface, from which it is then possible to deduce that portion of the mould involved in the solidification process after a fracture event. Referring back to Figure 9 by way of example, it is evident that the normal lap mark to lap mark surfaces to the left of the flaw are a fair reproduction of the mould length BL_1 in Figure 23. This suggests that shell fracture occurred at or close to B, the lower fracture edge moved by the amount of the stroke to L_1, and the admitted liquid solidified against the surface BL_1 forming a lap mark at L_1, and re-melting, or solidifying onto, an upper ring left adhered at B. On the right of the flaw in Figure 9, score marks run from lap mark to lap mark inferring that the fracture line of the shell was located in the area CD at F in Figure 23, and the region FL_2 was used to solidify a stroke length.

These examples of relating cast to mould surfaces permit the conclusion that in the typical case illustrated in Figure 23, fracture does not occur in the zone AB. The evidence suggests that in fact that area is at a temperature above the liquidus, and that initial solidification and strongest adhesion, occurs at B. The line of fracture of the shell probably varies between B through C during casting, so that the stationary ring of the shell may be of varying lengths in the zone BC. A firmer viewpoint might place the line of initial solidification at B and the fracture line at C where the majority of score marks originate as a result of the movement from that line of the lower fracture edge.

It can be readily argued that because the point of fracture of the shell is fixed within a narrow region of the mould length, that the upper ring must retain its size and position from one fracture event to the next. Since, however, heat is continuously extracted by the mould, it follows that the ring must undergo some re-melting during the extraction stroke, with the result that the net solidification rate of the ring will be much lower than for example material solidified against the mould wall immediately below the fracture line. Translating these points into schematic form in Figure 24 and interpreting solidification rates to obtain graphite nodule sizes in the shell, a picture is developed of a small mound of large nodule size at the tip of the shell, with nodule size decreasing from the fracture line to the last lap mark formed.

Returning to the question of the association of flawed areas with lap marks, it is apparent that if for some reason the fracture line moves locally up the mould toward the tundish, then the established upper ring, or a part of it, with its characteristic large nodule size, will be cast with that stroke, producing the observed transition of nodule size in the sub-surface structure of the bar. Examining this projected departure from normal transverse fracture behaviour more closely in Figure 25, it becomes possible to devise a mechanism for flaw generation. It is assumed that in the course of extraction loading of the shell, the upper part of the shell, above the normal fracture line, does not remain in close contact with the mould, but is pulled off the mould wall prior to fracture. The lower portion

that at some stage a continuation of the process becomes untenable, and the fracture site reverts to its original location thus allowing the cast-in cold shut zone to be withdrawn as a body. This switching of fracture site from below to above the flawed area of the shell may be explained in either of two ways. In the simplest of these, it is envisaged that the repeated intrusion of thin sheets of metal between the upper ring and the mould wall has the effect of prying the ring from the wall, i.e., reducing the frictional restraint to a point at which the entire upper ring, or a major part of it, is dislodged at a lower load than is required to produce fracture further down the shell. Alternatively one may consider the step-wise rotation of one of the original discontinuities toward the normal to the loading axis, so that at some point in time this suitably oriented notch itself nucleates fracture at a lower load than the rupture load of the shell below the flaw. In this event, the entire flaw area moves down the mould and a normal lap mark occurs between the tip of the flaw and the following liquid (Figure 25J). At the same time, the upper ring left adhered to the mould wall retains as it were the image of a discontinuity, so that the casting stroke which produces a flaw may very well start a new series of discontinuities using the remainder of one of the previous set as a "mould". There are a number of weak points in the above description of the mechanics of flaw generation, chief of which is the movement of the fracture line down the mould during the accumulation of discontinuities. This should displace the normal lap mark in the direction of casting prior to a flaw event, and as noted in observation d) the displacement is occasionally pronounced in the opposite direction. Another incomplete supposition is that at the core of the mechanism, namely the separation of the shell from the mould wall prior to fracture. If one accepts that the presence of cold shuts in the upper ring is adequate proof of such separation, then it might be expected that the lower fracture edge would also be separated from the mould, and that at the end of its stroke, the following liquid might produce a cold shut coincident with the lap mark, and angled to the surface as a mirror image of the generated flaw discontinuity. On the contrary, lap marks preceding a flaw event are sound and show no evidence of the lower fracture edge having been a part of a mechanism of flaw generation. It might be surmised, of course, that during the stroke sufficient re-melting of the lower fracture edge takes place to reduce the extent of liquid intrusion behind it, but such additional speculation in a subject already overburdened with guesswork, must be judged inadmissiable.

The proposed mechanism readily accommodates the majority of the observations listed, and can be simply modified to describe the appearance of single flaw discontinuities. It merely suggests how flaws may be formed, however, and has taken no account of why such phenomena are observed. Why, for example, are flaws a local event on the mould perimeter? Why does the upper ring separate from the mould wall before fracture, and in so doing nucleate a discontinuity. Why does the flawed upper ring become unstable with the result that it is cast on to the extracted lower part of the shell? It must be admitted at the outset that well-defined answers to these questions are not available in this present account, and that it will be necessary to further enlarge the number of proposals introduced into the discussion.

It will be argued that flaws occur at cold spots on the mould surface where local thickening of the ingot shell upsets the normal shell fracture path to generate the triaxial loading responsible for the twisting and separation of the upper ring before fracture. The stages of development of this proposal are as follows. Where conditions of radial symmetry of heat extraction exist, the shell shape at the end of a dwell period will likewise be symmetrical and the fracture path will be transverse through a constant wall thickness of the casting. The actual position of the line of fracture will be the result of the interaction of the intensity and length of the frictional restraint produced between the mould and the shell tip, and the shell properties of thickness and stress to rupture at various points along the mould. If it is now assumed that the fracture path may be defined in terms of a certain value of shell thickness, d, and that shell thickness itself is a simple function of distance from the shell tip, i.e., the point of initial solidification, then the effect of hot and cold mould areas can be predicted since the fracture path is a fixed distance from the point of initial solidification. That these simplifications are justified is readily confirmed by the appearance of lap marks in unbaffled horizontal casting in which the bottom of the mould is cooler than the top, and again in the case where an orifice in the mould baffle plate permits a jet of hot liquid to push the initial solidification point in the direction of casting. It is a simple step to envisage the effect on the fracture path of a single cold area on the mould wall. The transverse line of rupture of the normal shell section will change direction on encountering the thicker shell opposite a cold spot, and move upwards, i.e., towards the tundish, following the characteristic shell thickness 'd'. The resultant bulged lap marks are identical to those observed to precede a flaw (see Figure 9). Injecting a time element into this abnormal fracture mode, it is suggested that there is a stage at which the fracture path has circumscribed the normal part of the shell, leaving the cold spot of greater thickness as the last part to fracture. At this point non-axial stresses develop tending to twist the shell away from the mould wall before fracture occurs. These triaxial stresses may be inherent in the rupture pattern of the non-uniform wall of the tubular casting, or they may arise solely from mal-alignment of the extraction system. With respect to the latter, it has been observed that misplacement of the mould axis relative to the extraction roll axis may result in the support rolls imposing a rotational displacement of the casting during the extraction stroke. It is tempting to relate this directly to the evidence of the rotation of cold shut surfaces given above.

It should be noted in passing that the hypothesis of flaw generation requires some plastic deformation of the shell to occur during lifting off the mould surface, while in the previous discussion of normal cyclic fracture zero ductility of the shell was assumed. There are two possible ways around this anomaly. Obviously the entire shell may undergo some deformation prior to rupture, this being restricted to a uniaxial vector in the case of normal fracture. Alternatively, there may be a difference in ductility between the fine nodule zone of the normal fracture path, and the large nodule zone associated with flaws so that the assumption of negligible ductility in normal fracture may still be used, and the displacement of the larger nodule zone may be ascribed directly to its ability to exhibit some deformation prior to fracture.

The process of flaw generation may be summarised as follows:-

1. Due to local thickening of the ingot shell, normal cyclic fracture is interrupted and the shell is pulled or twisted off the mould wall in that area before completion of fracture.

2. Incoming liquid forms a cold shut behind the disturbed part of the upper ring of the shell.

3. These steps are repeated on subsequent extraction cycles producing a series of overlying cold shuts in the stationary upper ring of the shell.

4. Finally, this flawed area of the upper fracture ring becomes unstable by virtue of one of the original discontinuities becoming an active fracture path, and the flawed metal is cast as part of the extracted ingot shell.

A corollary to the above hypothesis would be that in the absence of anomalies in cooling and solidification rates, and in the unidirectional loading of the shell during extraction, no cold shut flaws could appear on the cast surface. The possibility of achieving these conditions will be discussed below. (Sections 6.3, 6.4 and 6.8).

The final step in this examination of flaws is a description of attempts to verify the developed hypothesis experimentally, and to relate the overall picture with data on the solidification rates of continuously cast iron. It has been suggested that the upper fracture ring contains the larger graphite nodule size observed when a flawed section of the upper ring is removed with the casting. It follows therefore that the large nodule zone is a characteristic of the upper tip of the shell left in the mould after each fracture event. In order to confirm this inference it would be necessary to obtain the upper ring, either by stopping the entire casting system and sectioning the resultant freeze-up from the mould, or by adjusting casting conditions to ensure that the ring was removed with the casting. The latter objective was approached by extending the dwell period of one casting cycle so that the solidification front and fracture path would move up into the nozzle and the following fracture event would be above the normal point of initial solidification. The previous upper ring would then be extracted as part of the casting. Applying this technique to the area of flaw generation, it was proposed that an extended dwell period be imposed some time after an observed flaw event, preferably just prior to the expected appearance of a cyclic flaw. If the general hypothesis is correct, the extended dwell should advance the next fracture path above the pre-existing flawed upper ring, resulting in the controlled production of a flawed surface and the presence of large nodules in front of the lap mark on the unflawed part of the bar periphery.

Two attempts were made to cast the upper ring in order to prove that it contained large nodules and latent flaws. Both were unsuccessful in this primary objective because in one case the overall mould length was one inch shorter than normal and in the other the extended dwell period employed was too long, with the result that the shell extended back to the baffle plate closure at the tundish end of the mould. On the stroke following the lengthened dwell period, the relatively cool flat tip of the shell in contact with the baffle plate moved down the mould. Incoming liquid was unable to weld completely to the planar face of the shell, leaving a large radial discontinuity on the bar periphery (Figure 26). Such radial "cracks" may be associated in all cases with solidification against the baffle plate and are not to be confused with the transverse thermal stress cracking found in other continuous casting systems and products.

7. Conclusions

a) Surface flaws have been identified as cold shuts formed during the withdrawal step of the casting extraction cycle by the radial displacement of the solidified shell away from the mould wall.

b) The cause of this displacement may be a combination of local thickening of the shell in areas of high heat transfer, leading to non-axial tearing of the shell during cyclic fracture: and non-axial loading of the shell due to misalignment of the extraction system.

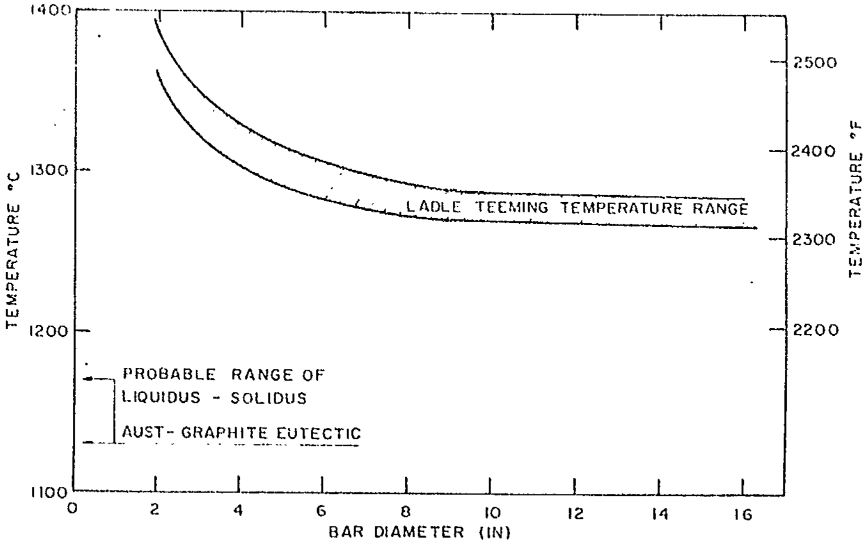


Figure 1. Specified pouring temperatures from transfer ladle to tundish.

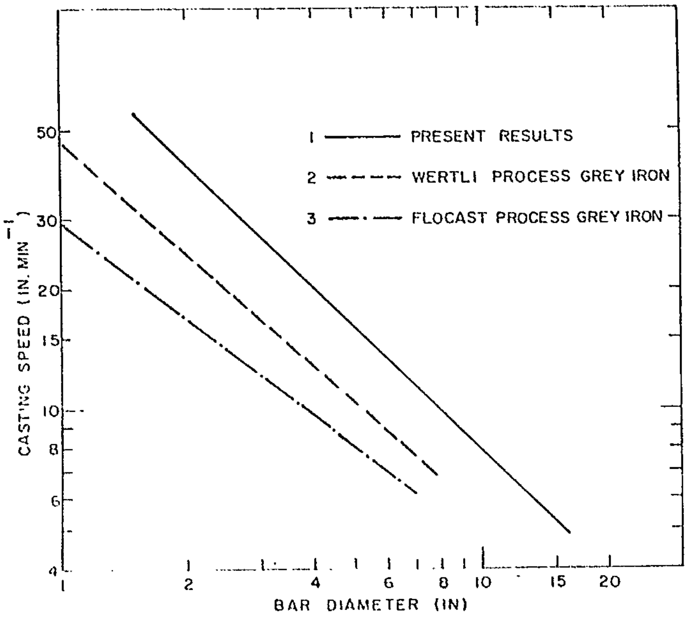


Figure 2. Average casting rate for various bar sizes. Data for two proprietary horizontal casting machines are shown for comparison.

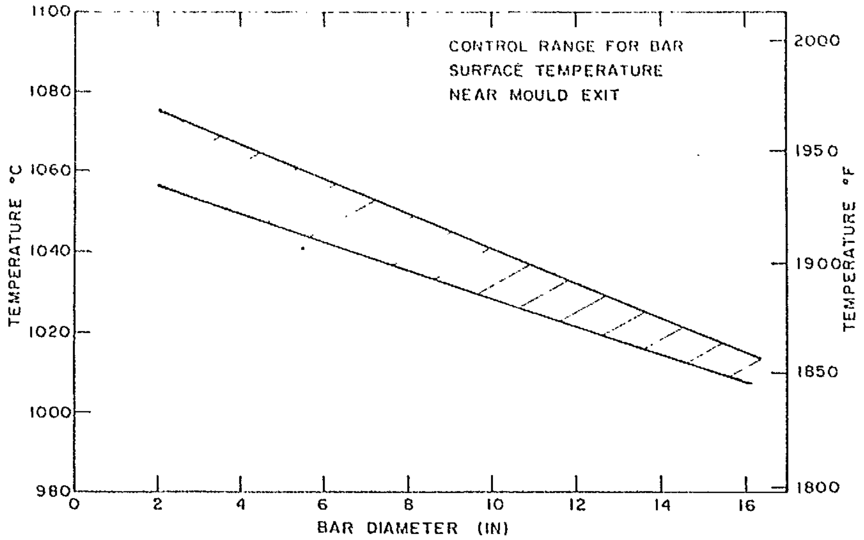


Figure 3. Target range for maximum top surface temperature of bar near the mould exit.

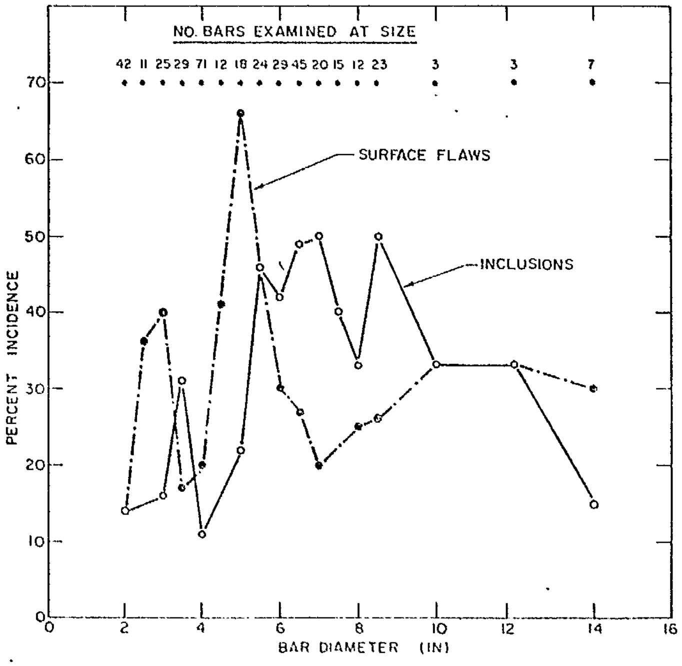


Figure 4. Incidence of flaws and hard spots revealed by machining cast bar.

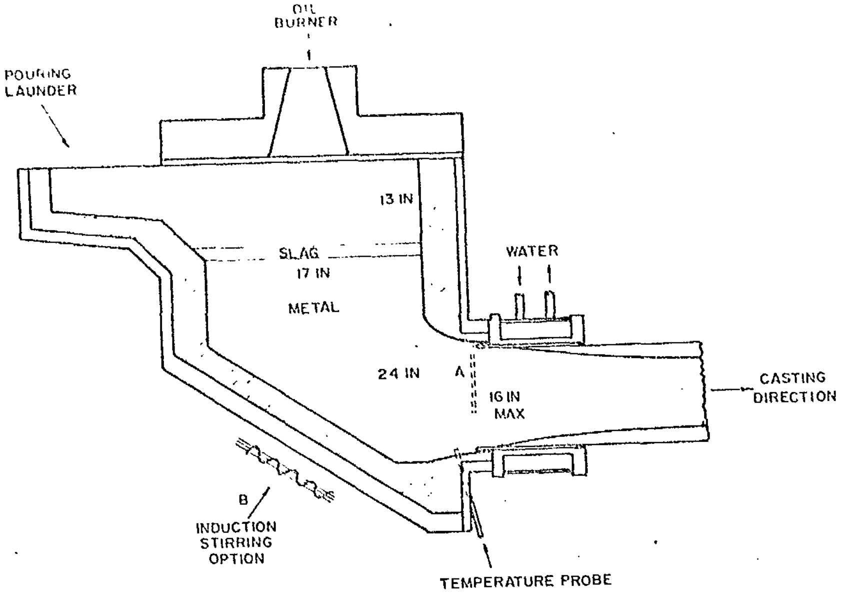


Figure 5. Sketch of tundish and mould assembly. The bath cross-section at the slag-metal line is approximately 17 x 17 in.

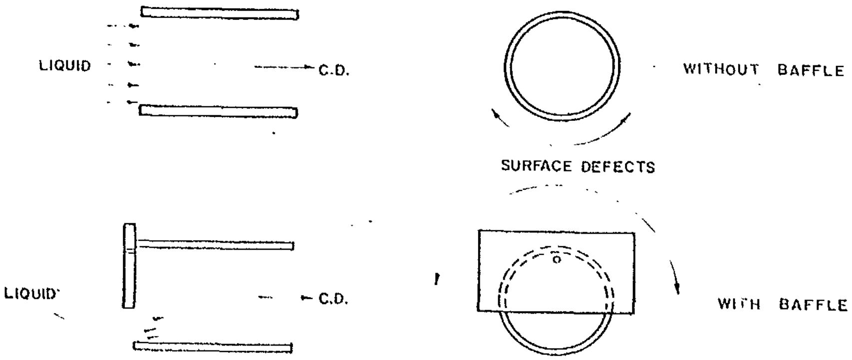


Figure 6. Illustrating the redistribution of surface defects by use of a baffle.

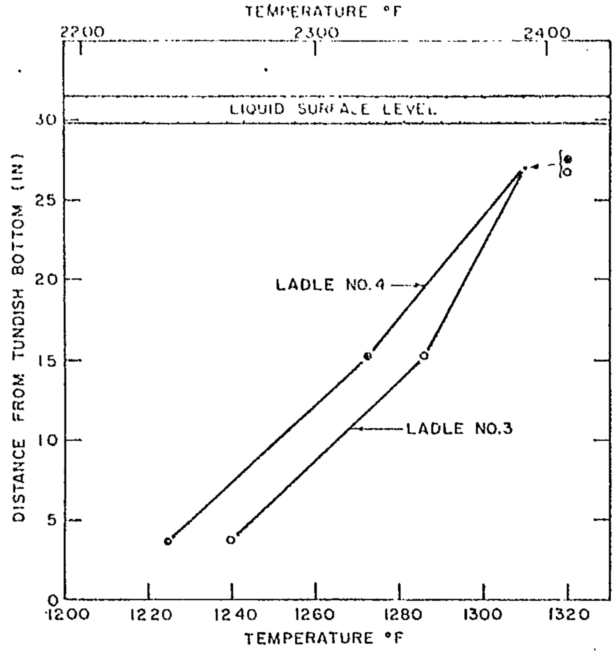


Figure 7. Temperature gradient from top to bottom of tundish during casting.

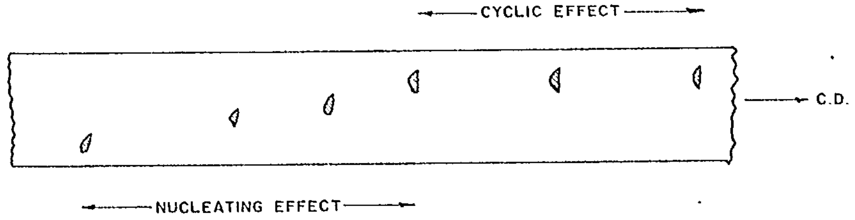


Figure 8. Sketch of flaw appearance on hot bar.

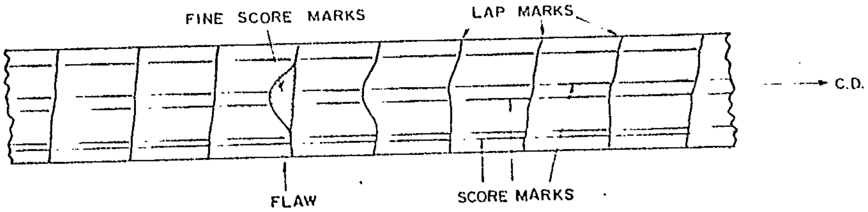


Figure 9. Illustration of the relationship between a surface flaw and the normal score and lap marks on the bar surface.

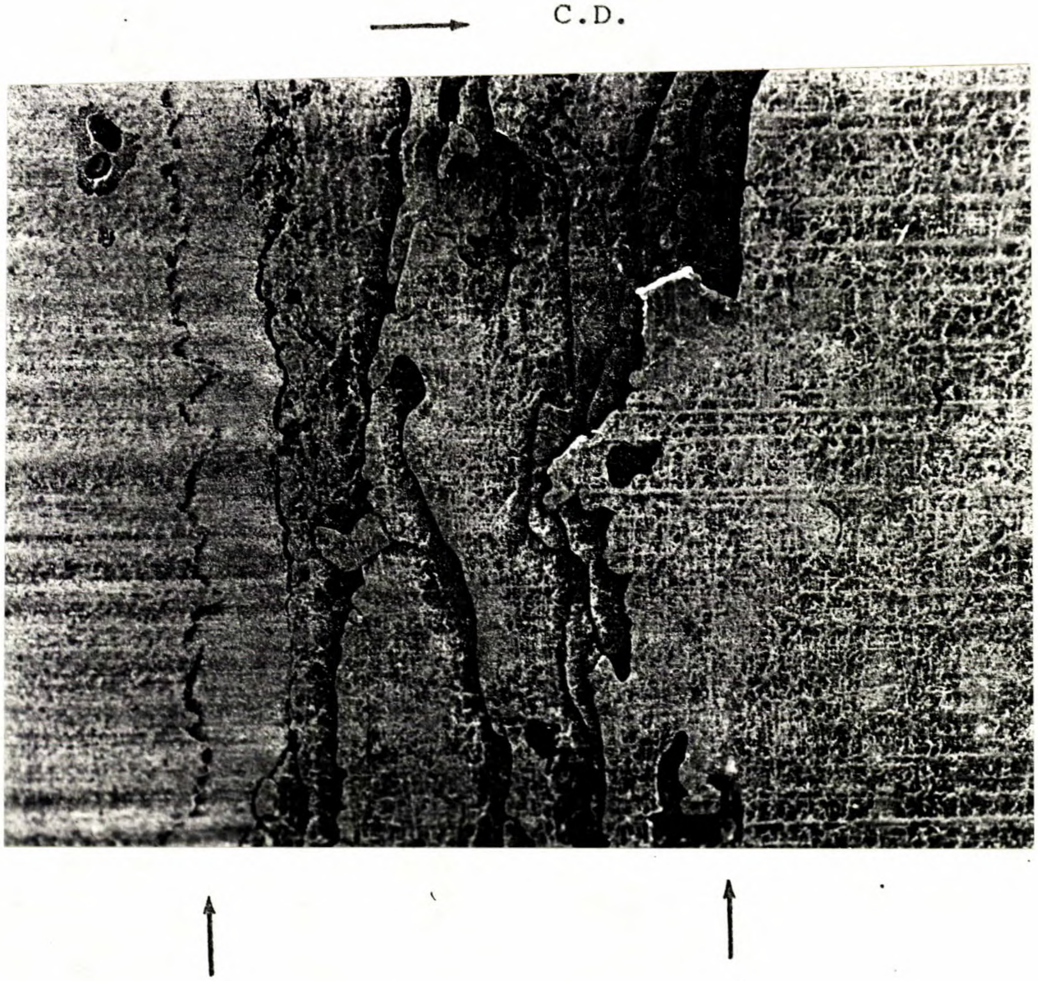


Figure 10. Macrophotograph of flaw on bar surface showing the layers of overlapping sheets of cast metal. Approx. X4.

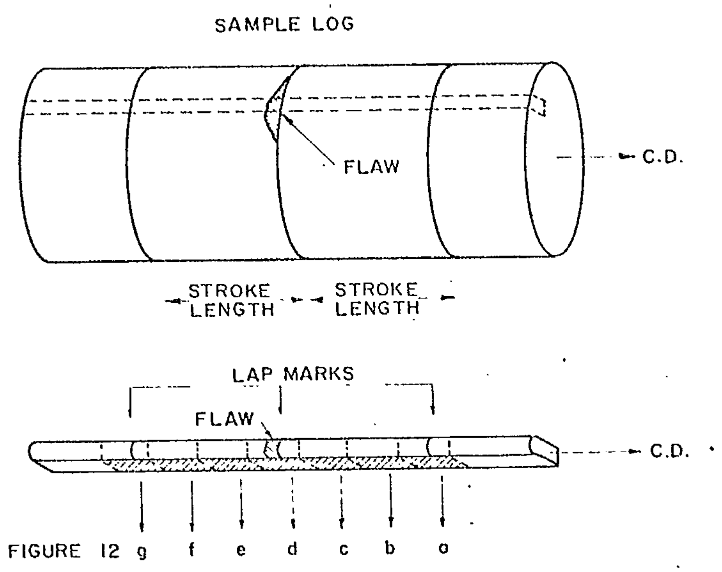


Figure 11. Each sample log containing a flaw was sectioned as shown for metallographic examination. The procedure is illustrated by the micrograph series of Figure 12. The shading indicates the face polished for examination.

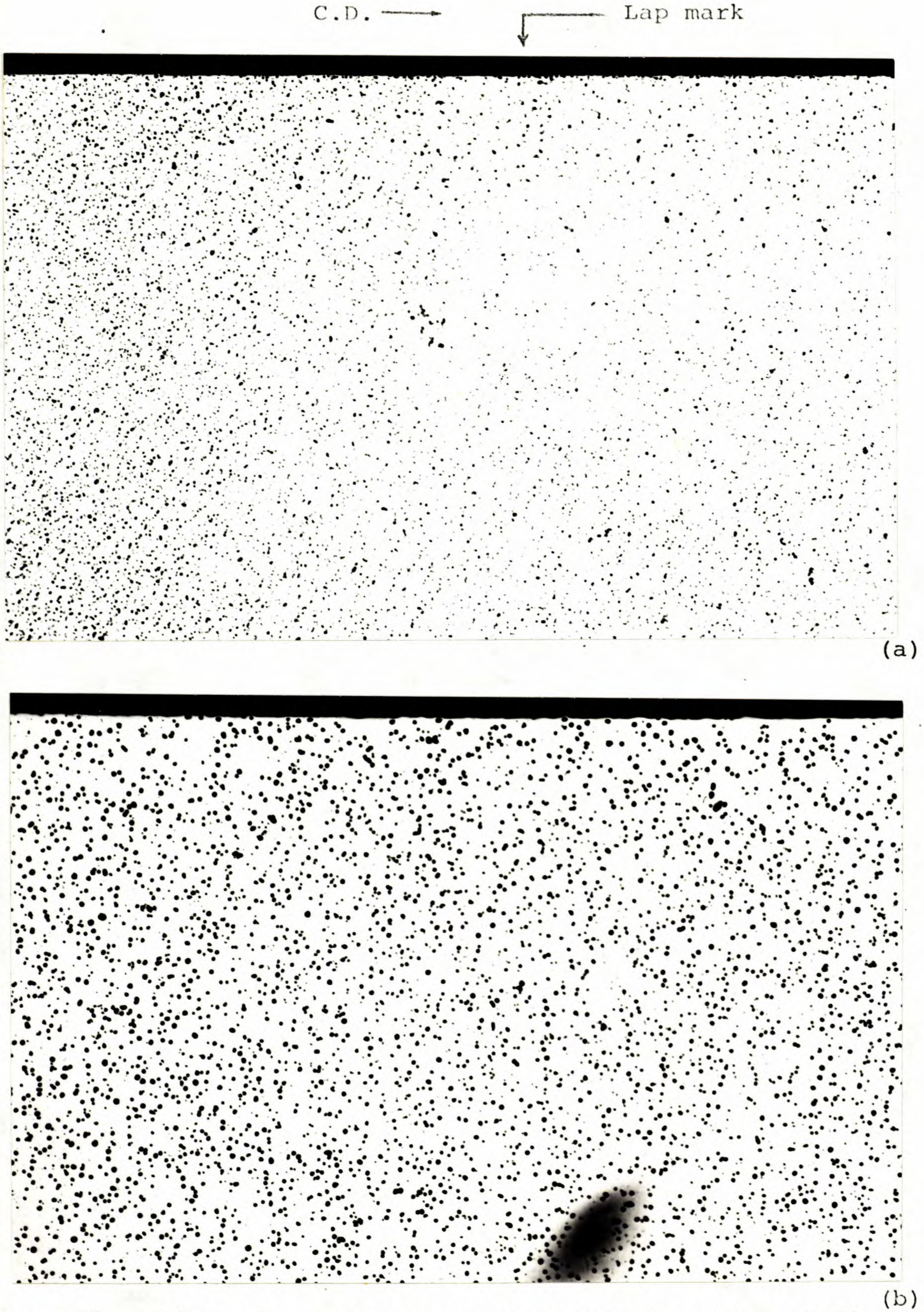


Figure 12. Sub-surface microstructures from locations indicated in Figure 11. Unetched X20
Casting direction left to right.

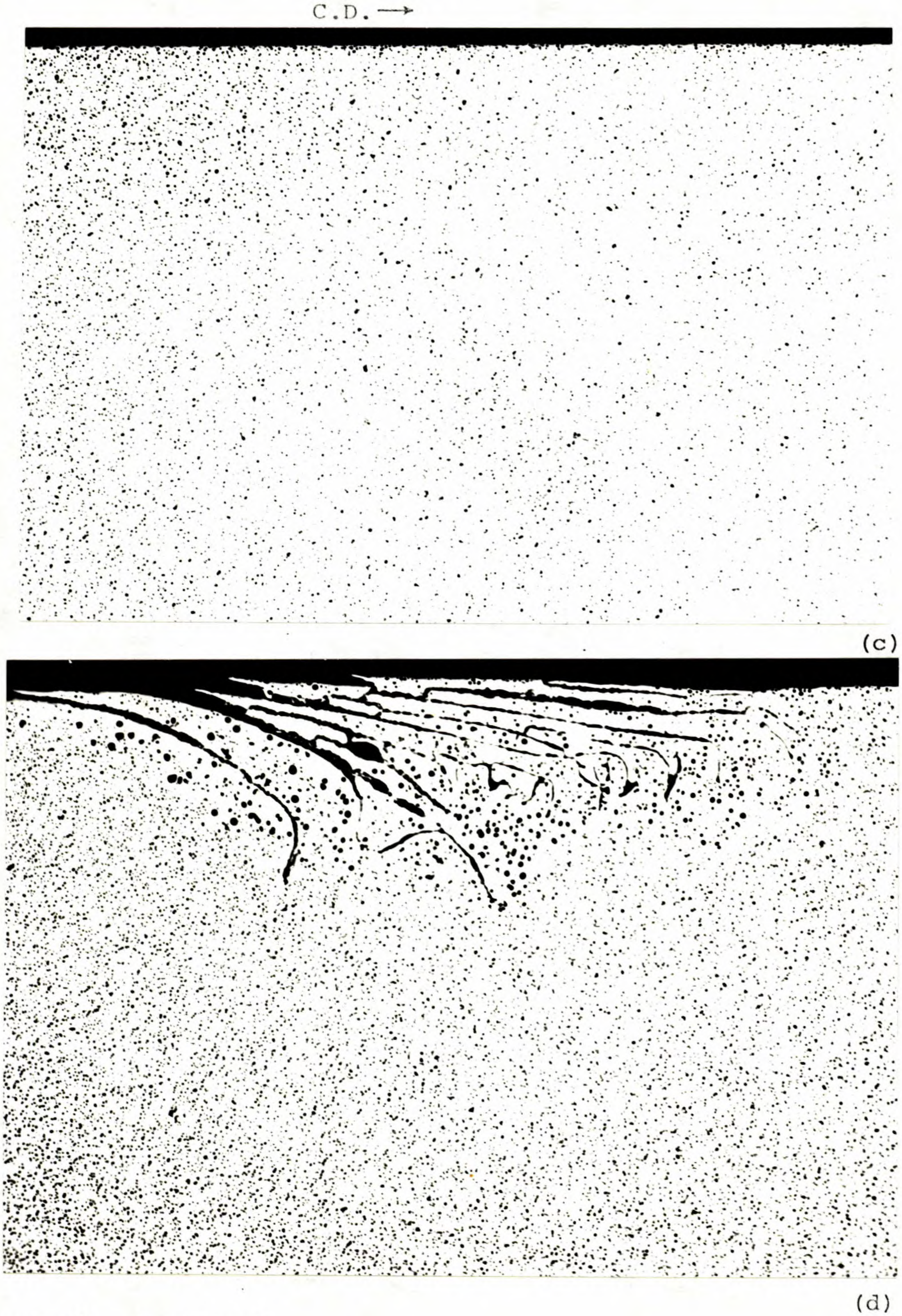


Figure 12. Continued.

X20

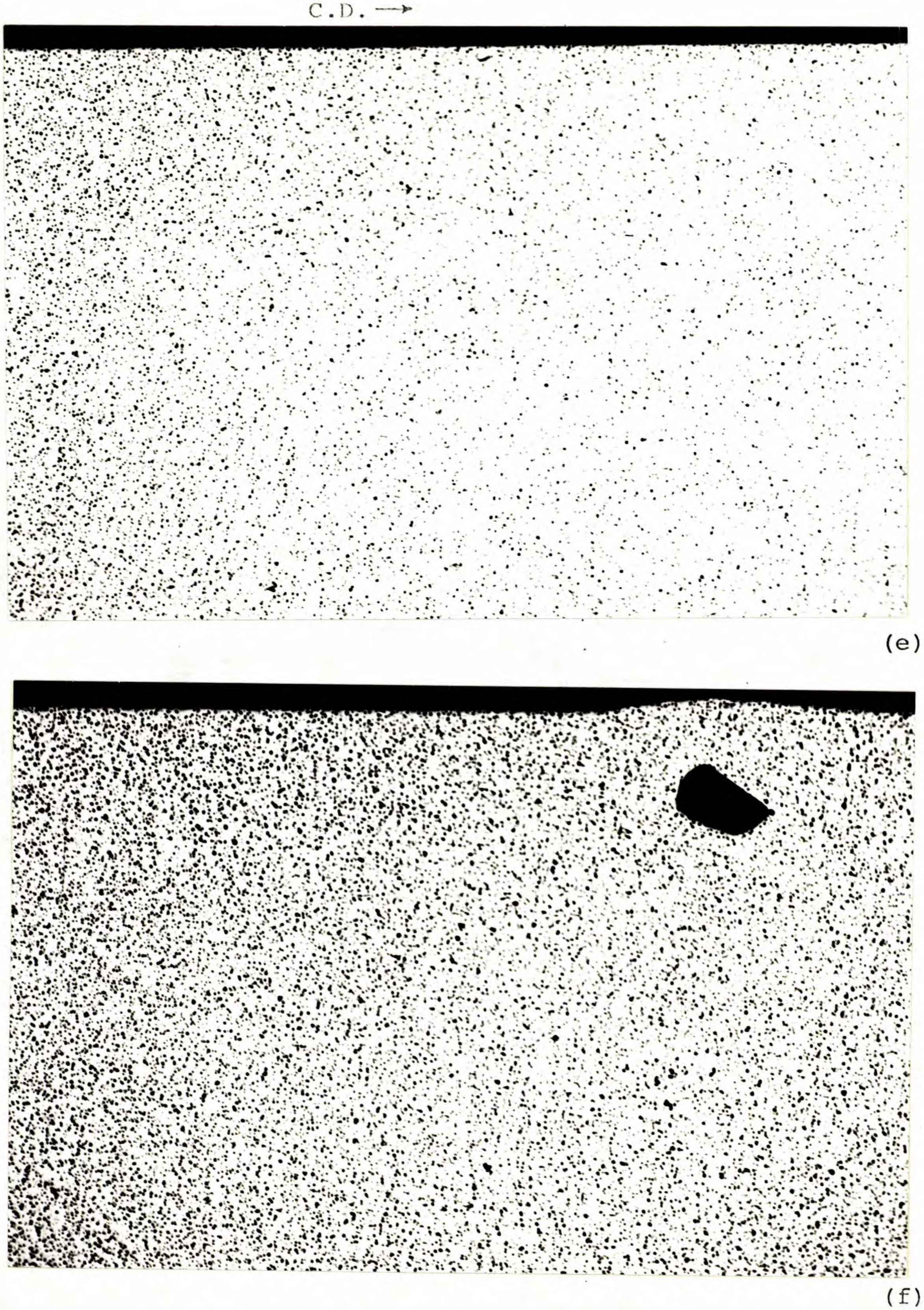
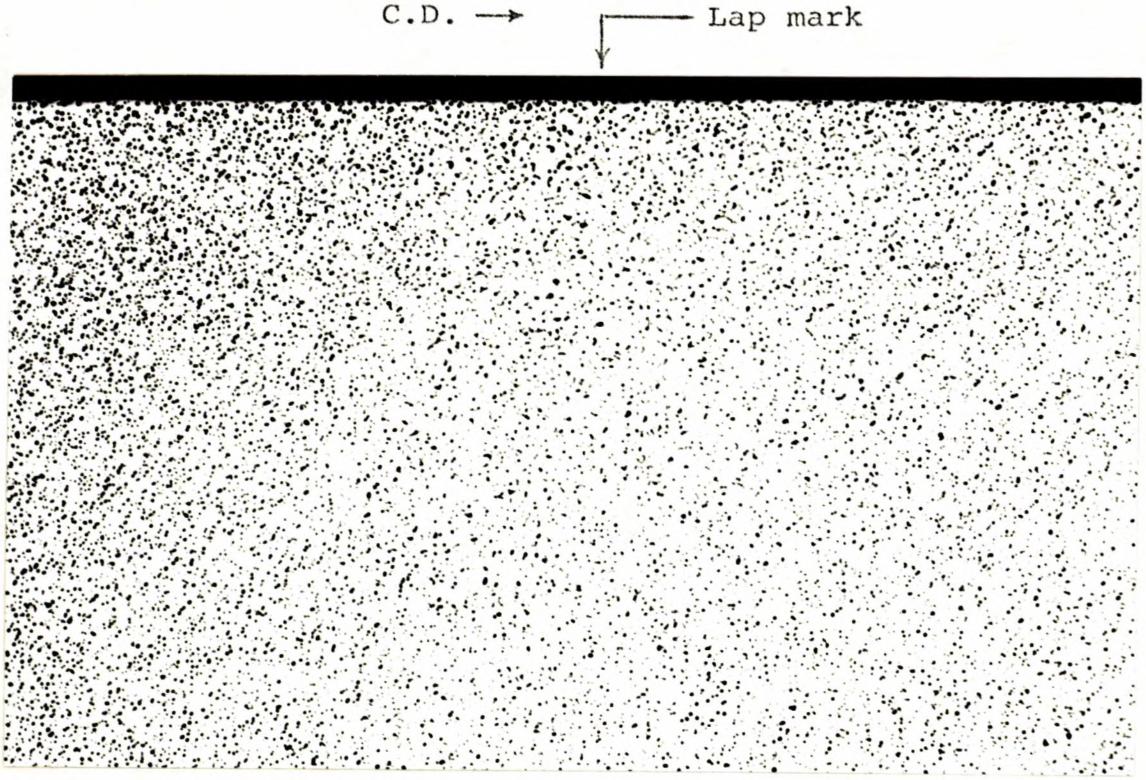


Figure 12. Continued. The sub-surface porosity in (f) has produced surface deformation. X20



(g)

Figure 12. Continued. X20

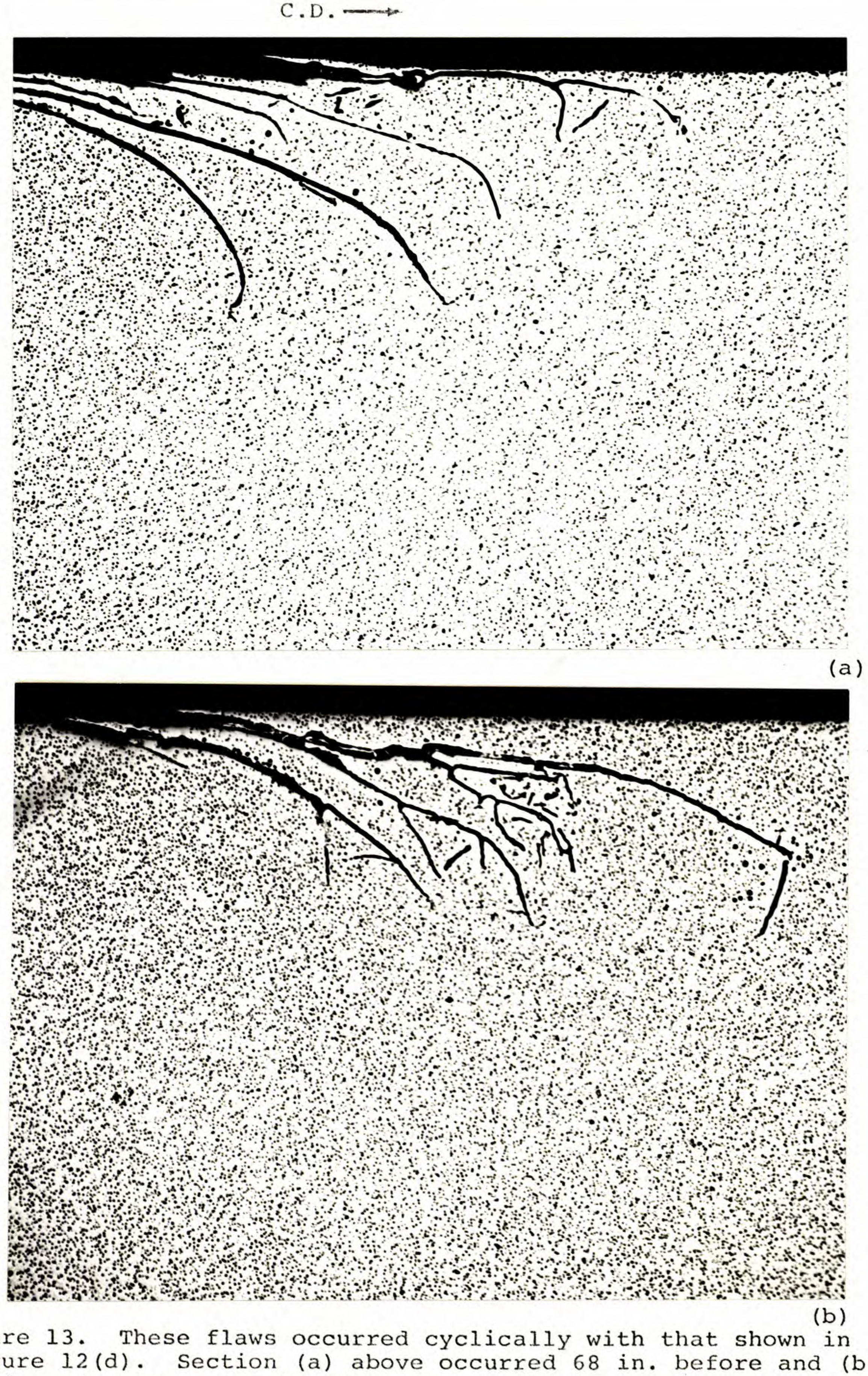


Figure 13. These flaws occurred cyclically with that shown in Figure 12(d). Section (a) above occurred 68 in. before and (b) 68 in. after the flaw in Figure 12(d).

Unetched X20

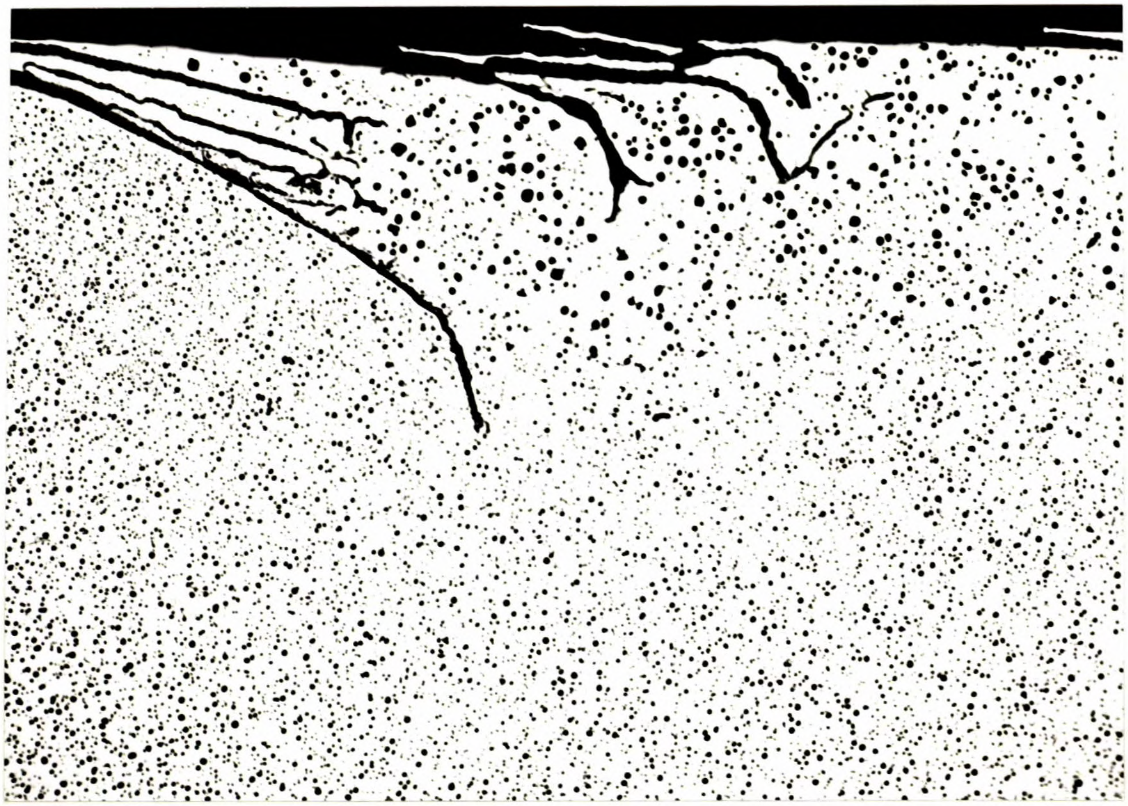


Figure 14. An example of a multi-discontinuity flow associated with a sub-surface zone of large graphite nodules.

Unetched X20

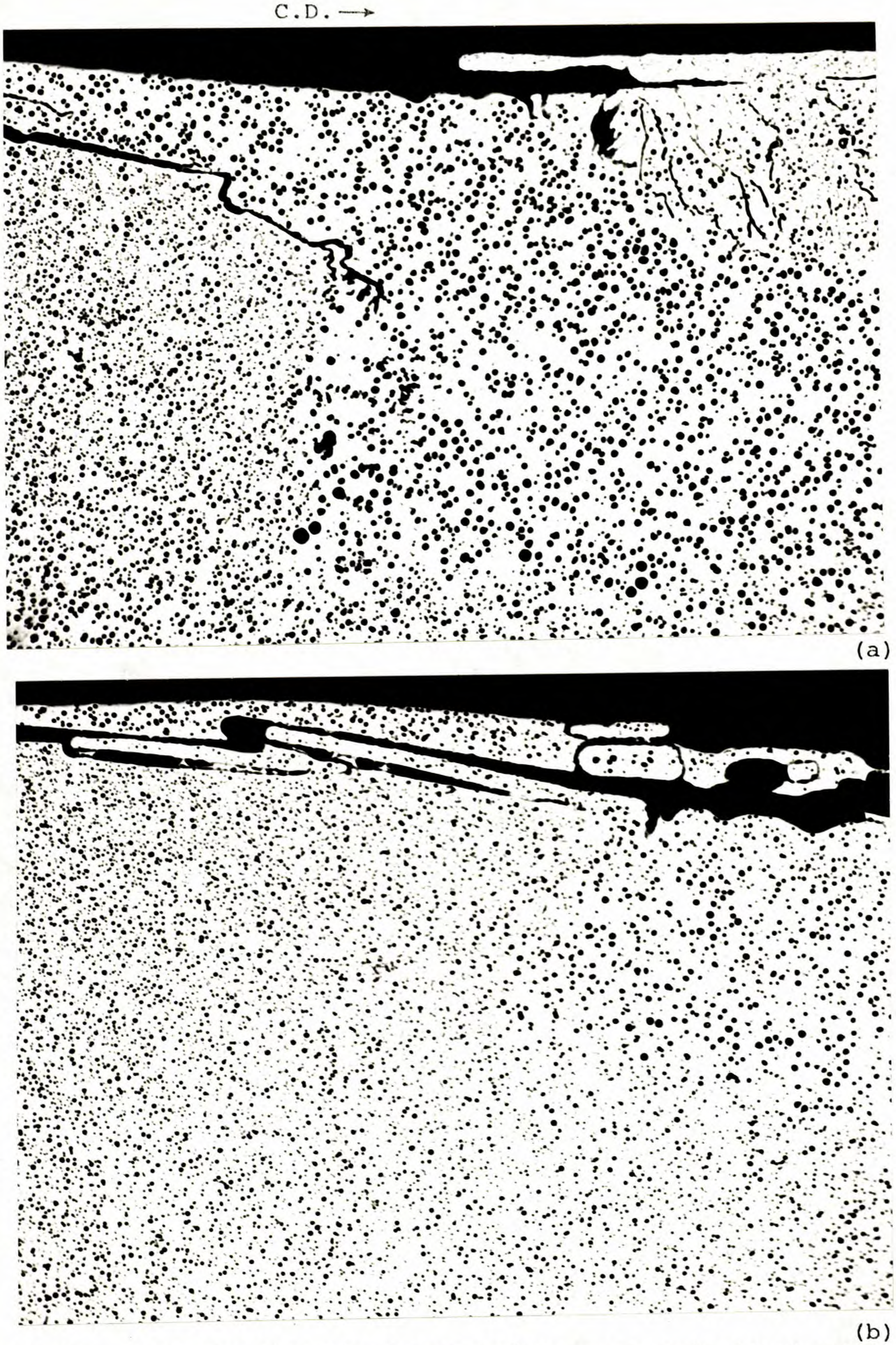
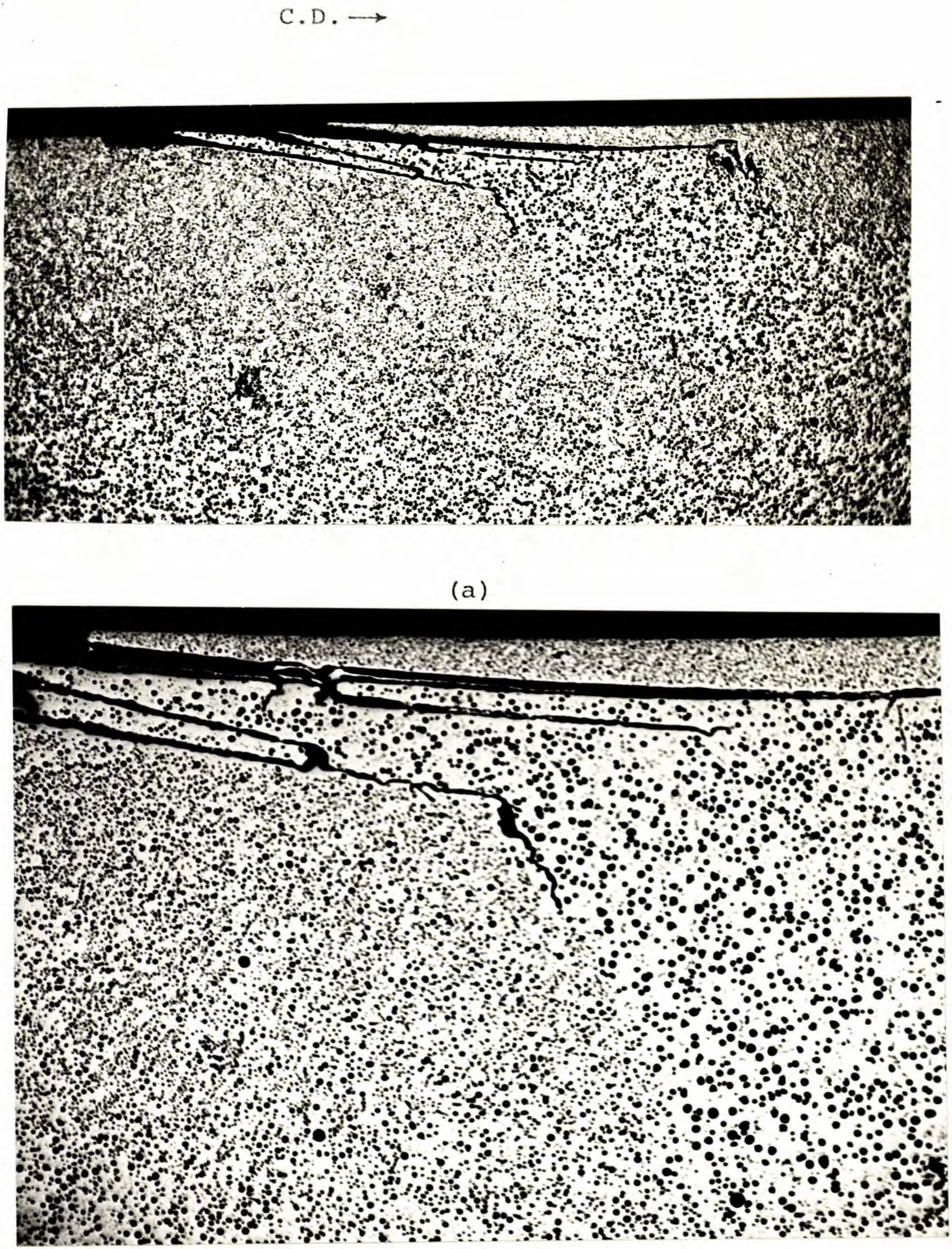


Figure 15. Illustrating the large nodule area coincident with flaws and the radial nodule transition boundary below the trailing discontinuity.

Unetched X20



(a)

(b)

Figure 16. A similar flaw to previous examples, showing in (a) at X8 magnification, the shape of the zone of larger graphite nodules, and in (b) at X20 magnification, the distinct boundary at the trailing discontinuity.

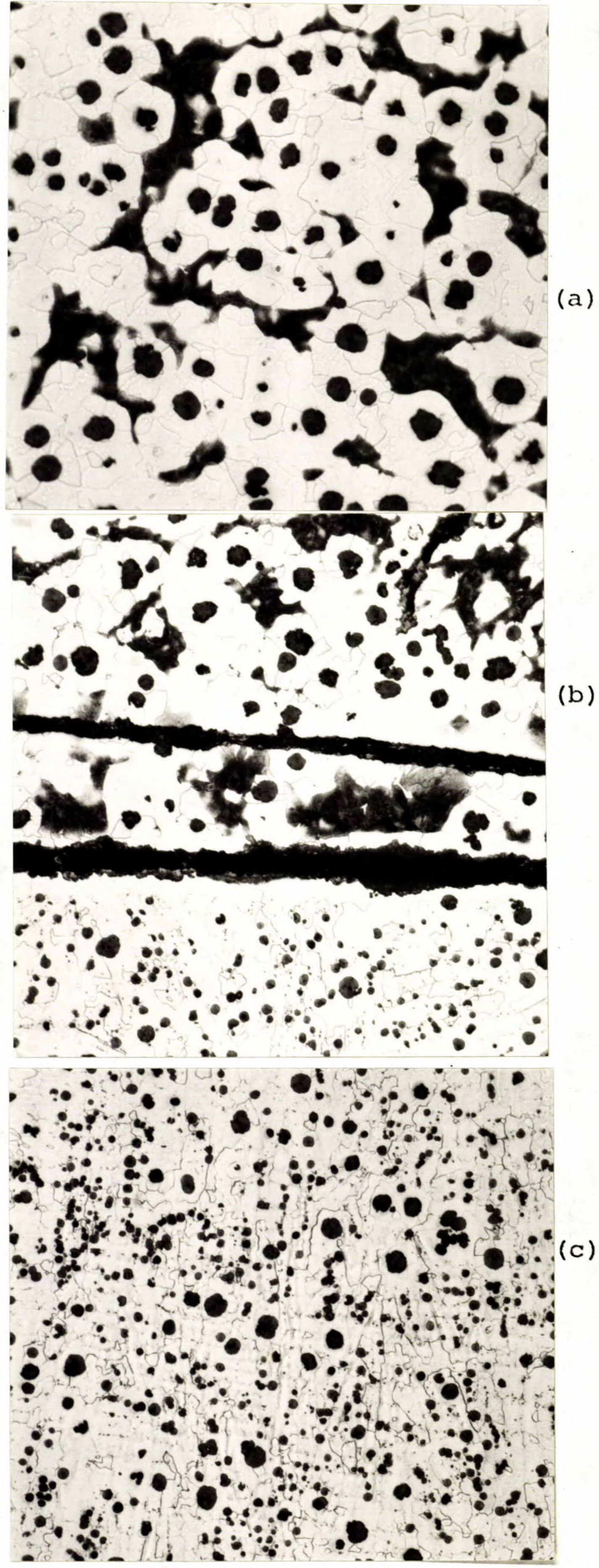
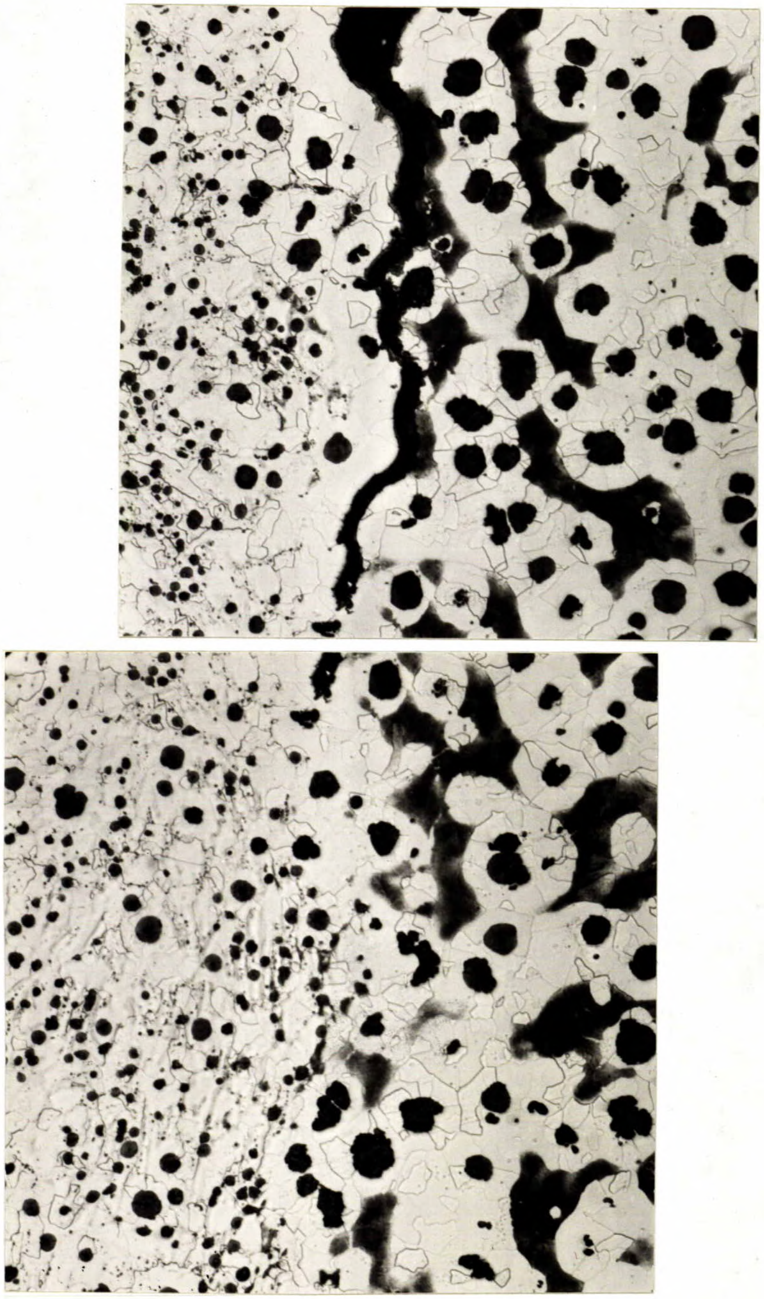


Figure 17.

Traverse across discontinuity boundary of the flaw shown in the previous figure. The large nodule zone shows a prior austenite grain size and a higher volume of pearlite.

Etched 2% nital. X100



Etched 2% nital X100

Figure 18. Detail of the root of the trailing discontinuity of the flaw in Figure 16, showing continuity of structure across the nodules transition boundary.

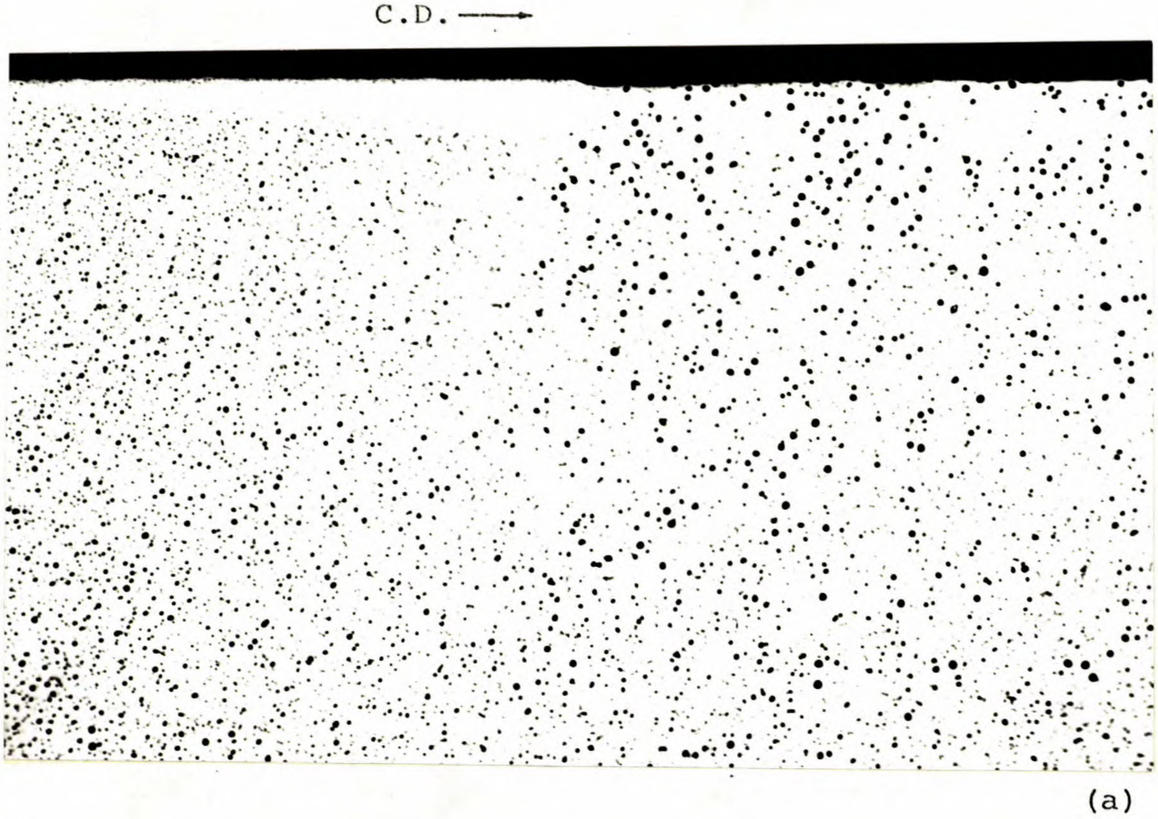


Figure 19. Two examples of abrupt changes in graphite nodule density occurring below a surface lap mark. Unetched X20

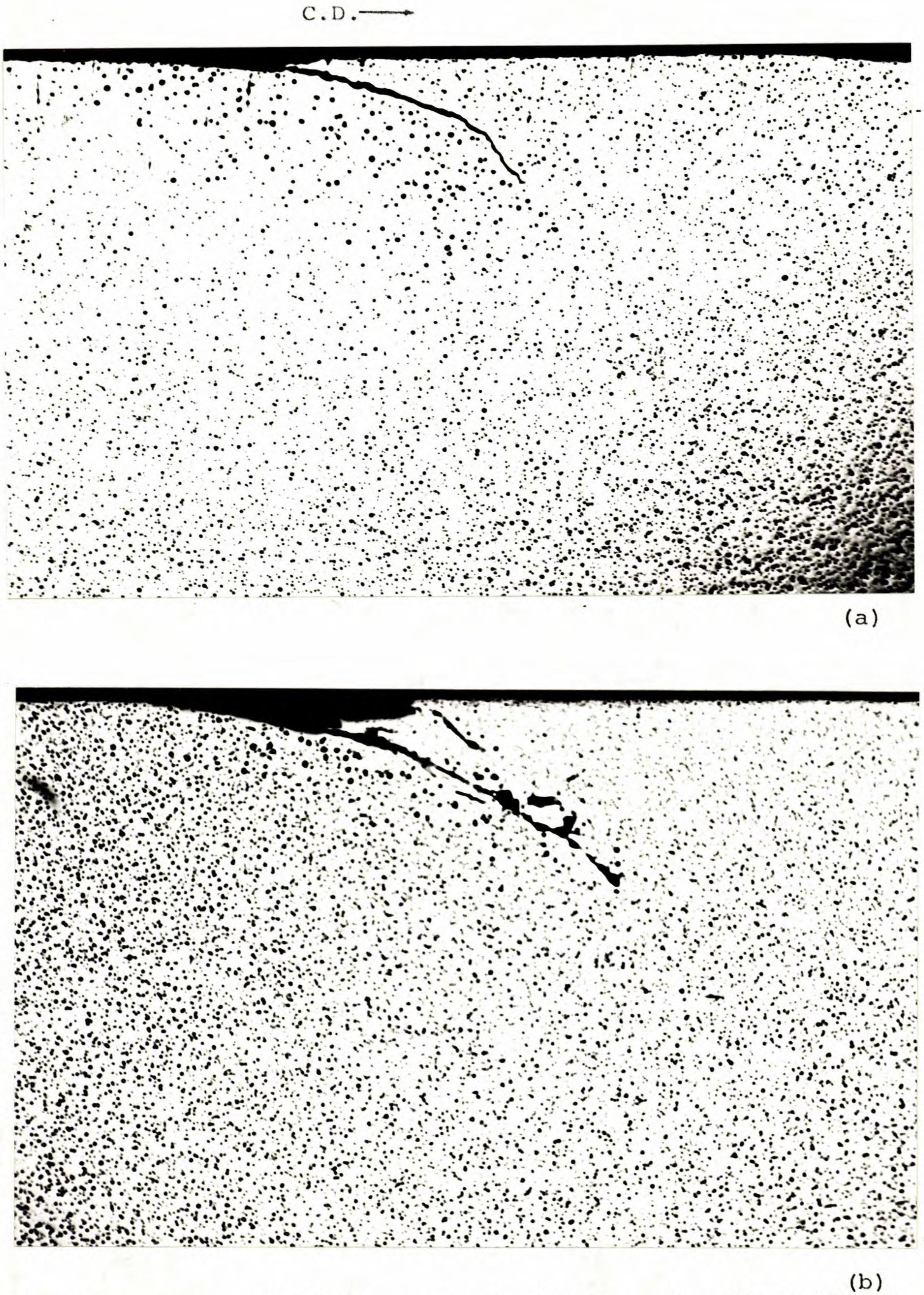
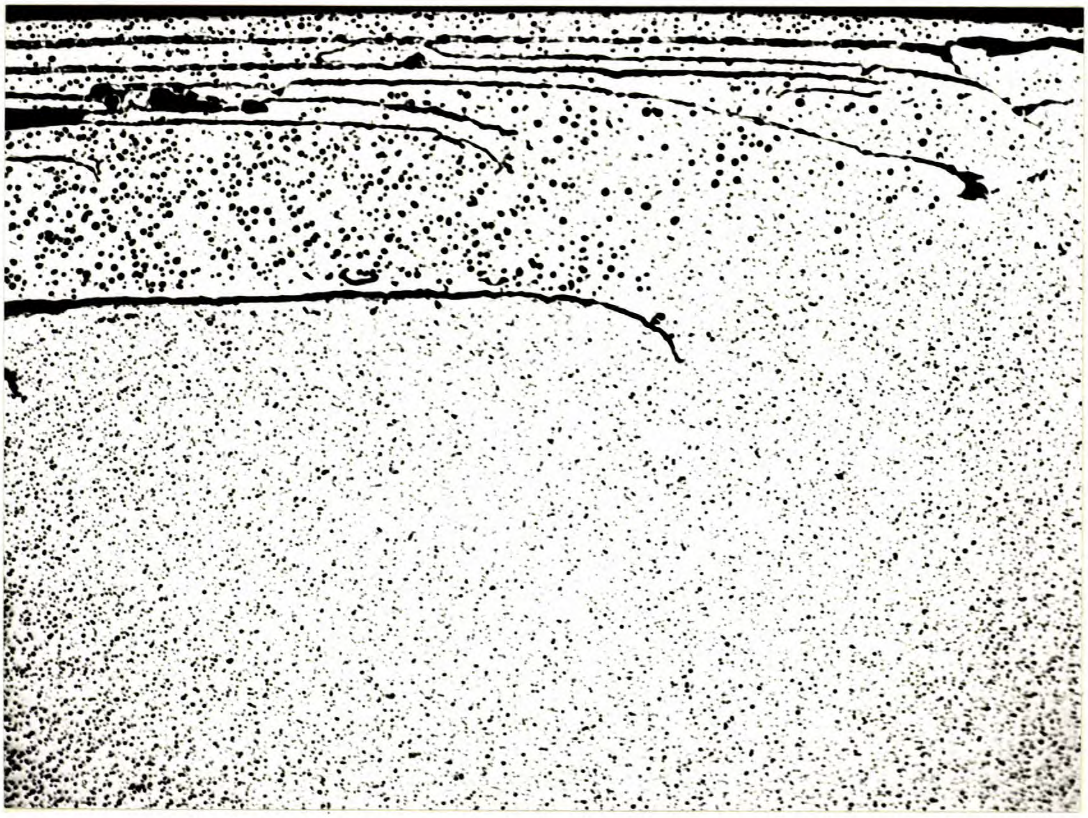
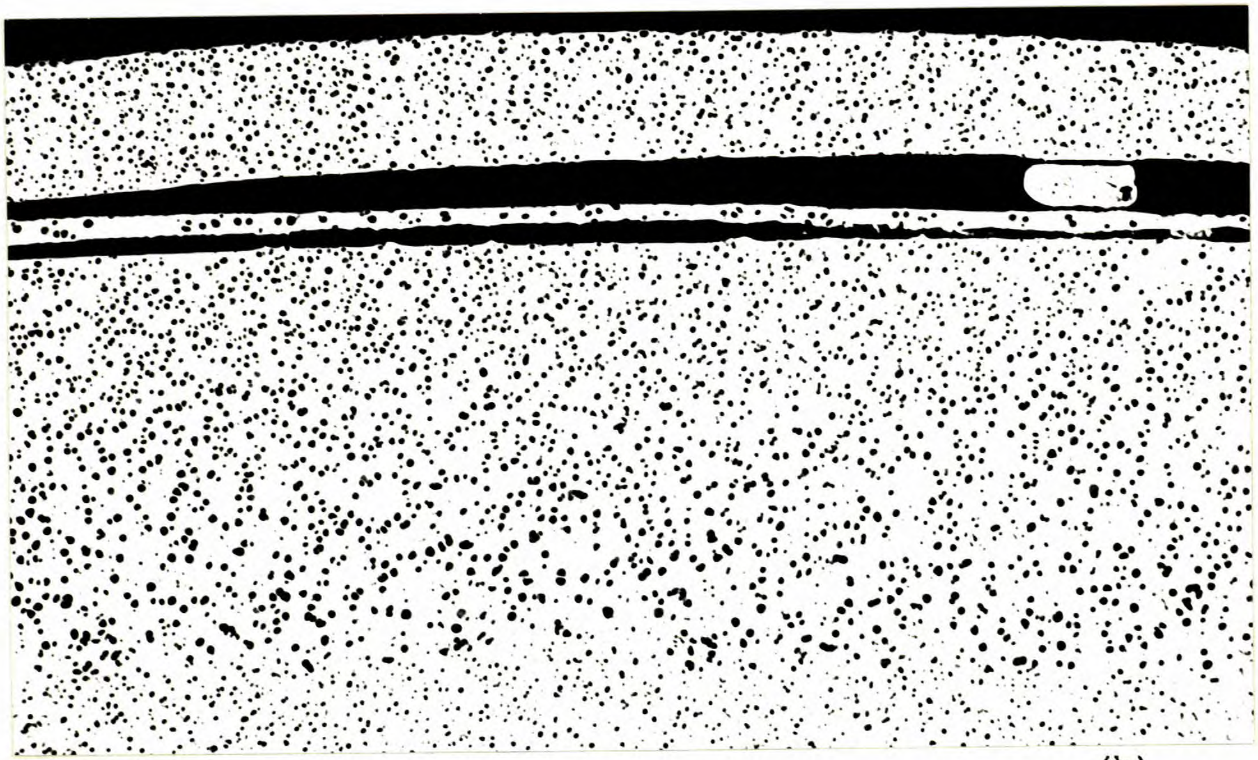


Figure 20. Flaws exhibiting a single leading edge discontinuity.

Unetched X20



(a)



(b)

Figure 21. Transverse sections of the flaws previously illustrated in Figure 12(d) and 15(a).
Unetched X20

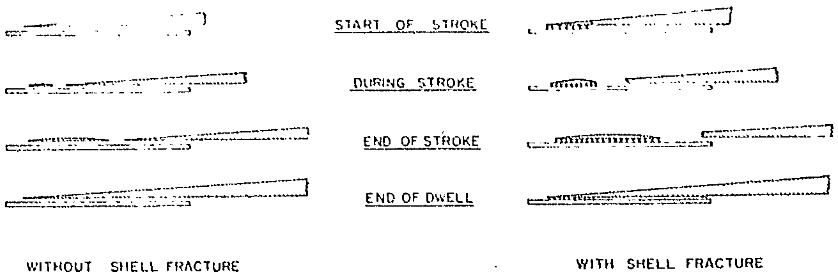


Figure 22. Comparison of ingot shell shape with and without fracture of the shell.

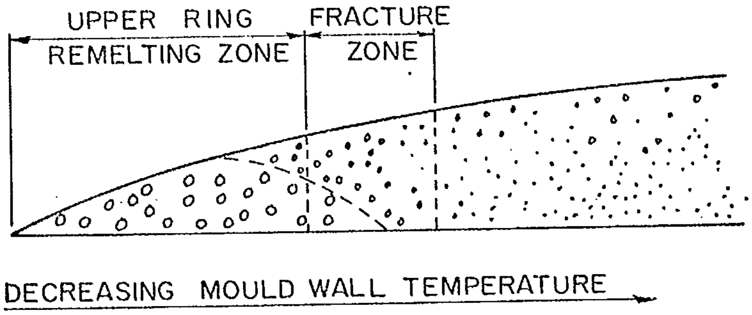


Figure 24. Model of nodule density variations with position in the mould.

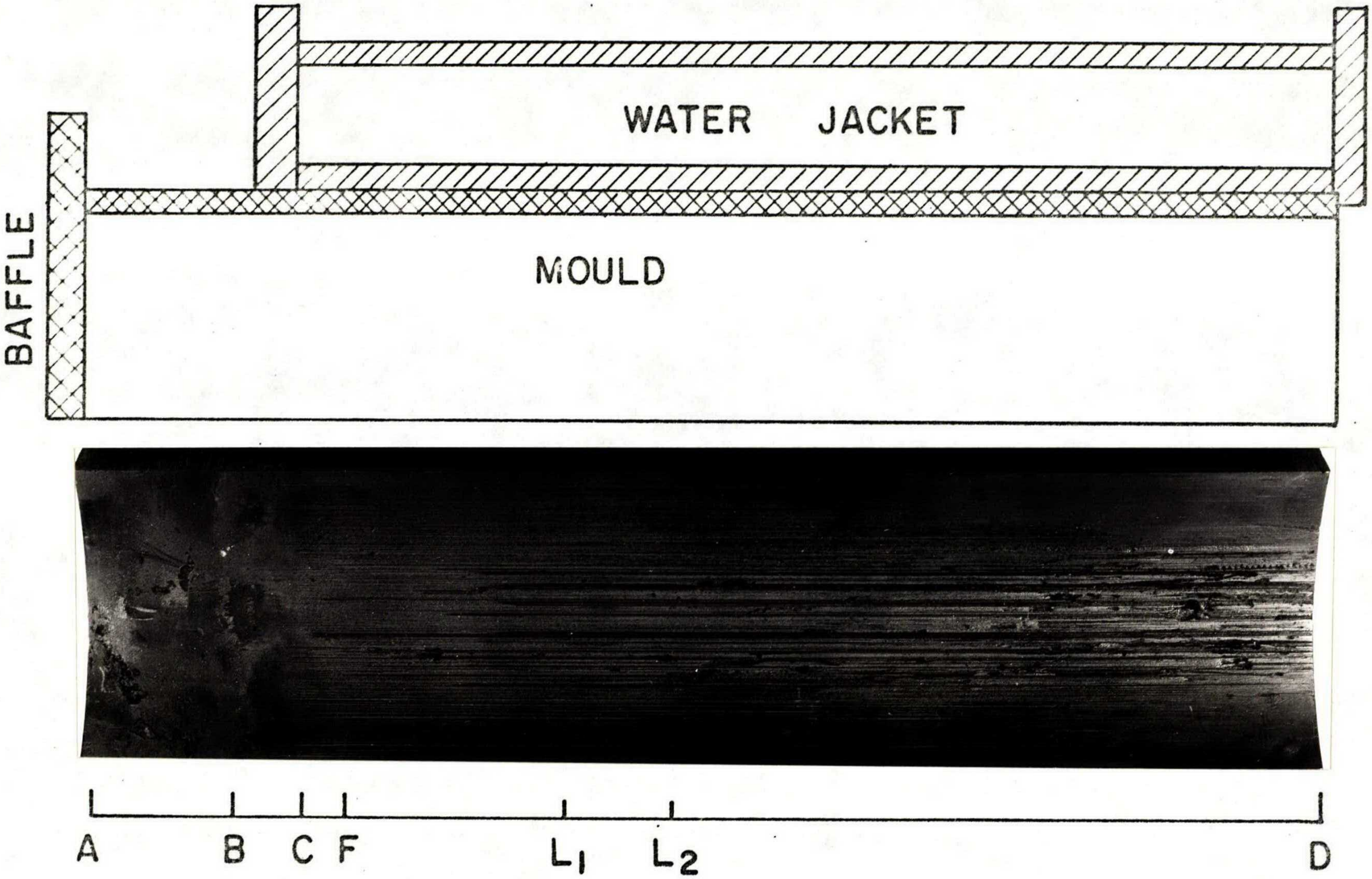


Figure 23. Photograph of a section of mould wall related to its position in the cooler. The zones AB, BC, etc., relate to shell behaviour during extraction as described in text.

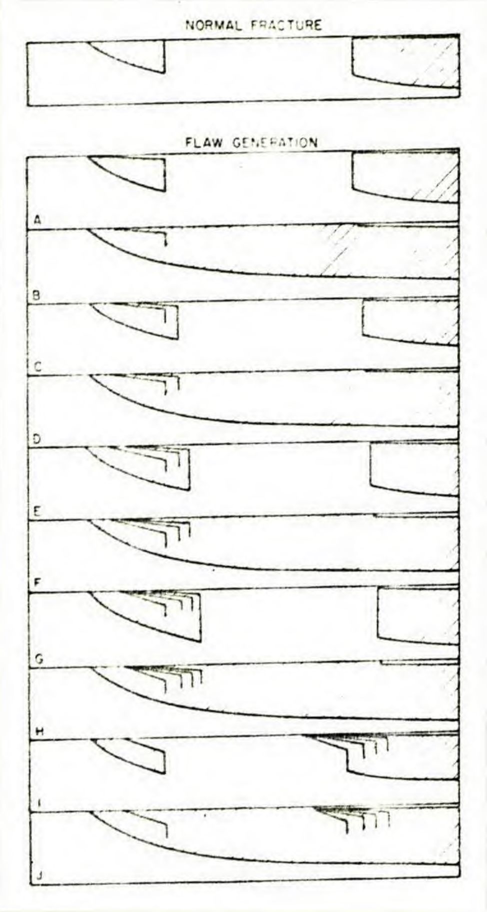


Figure 25. Model of flaw generation showing separation of the upper ring from the mould and the intrusion of fresh metal into the gap to create a discontinuity.

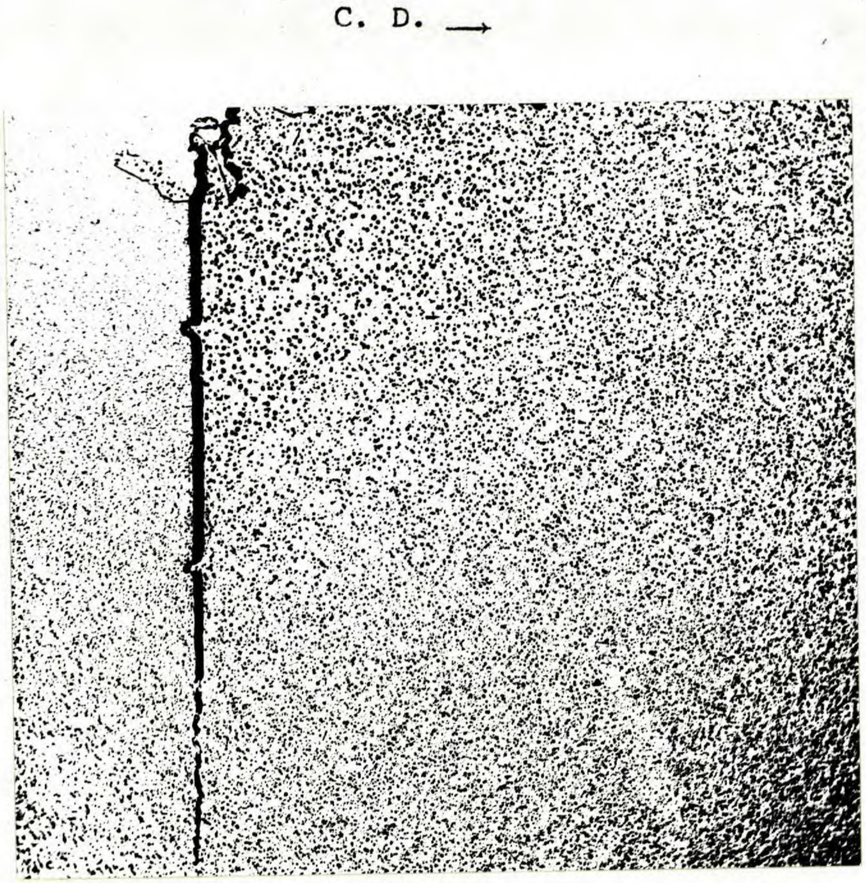


Figure 26. Radial discontinuity formed by solidification against the baffle plate; subsequent movement of this surface down the mould; and incomplete welding of the following liquid.

Unetched X8

APPENDIX 1

From P.M.D.

The existing "state-of-the-art" and proposed investigations may be discussed conveniently with direct reference to the two chief problems, surface cracking and slag inclusions:

1. Surface Cracking

Flaws appear to originate primarily on that perimeter of the mould surface shielded by the baffle plate and may be associated with the inclusion, on the surface of the moving shell of the casting, of a cold solidified island to which newly introduced liquid has difficulty in joining. The following are recommended:

(a) Metallographic analysis of cracked and uncracked skin sections to derive a hypothesis for flaw origin.

While such an analysis is being pursued here, various ad hoc experiments aimed at increasing the temperatures of mould-solid shell interaction should be carried out. These are:

(b) Evaluation of the effect of superheat on flaw incidence using existing mould/baffle design.

(c) Alteration of baffle design to eliminate dead zones of liquid metal behind the baffle. This approach would include altering the mould/cooler design in such a way as to increase mould wall temperatures in the area of initial solidification.

(d) Evaluation of the effect of withdrawal parameters on flaw incidence, viz., examine the effects of stroke length per se, and the effect of cycling stroke lengths.

(e) Examination of the effect of mould surface on flaws. Since it is probable that the appearance of a flaw represents a disruption of the normal cyclic fracture and re-healing behaviour of the ingot shell, the mechanical aspect of mould-billet interaction may be looked at from the points of view of mould preparation, mould vibration, and negative stripping of the ingot shell.

2. Slag Inclusions

From preliminary work on our water model it would appear that the major source of inclusions is related to the high liquid velocities into the mould cavity inherent in the use of the baffle. Since the latter is indispensable from the viewpoint of temperature equilibration in the liquid sump and subsequent ease of control of the casting process, we must aim at the elimination, or control, of entrained slag in the tundish by examining the following:

(a) The effect of pouring tundish additions only during a portion of the casting dwell period.

(b) The minimisation of slag in the tundish by improved liquid metal handling prior to ladle pouring, and by inoculating in the ladle rather than in the tundish.

(c) Changes in tundish design to increase the dwell time of liquid iron in the holding furnace and so increase the available flotation time for entrained slag. This approach would employ a water model to evolve new design features.

3. Definitive Experiments

In a third group of tests rejoicing under the above title, the object will be to more fully define the phenomena involved in horizontal casting. These experiments are not intended to solve problems, but rather to help in their understanding.

(a) Heat transfer analysis of mould-cooler combination with simultaneous evaluation of average rate of solidification using radio-tracers.

(b) Heat transfer work on cast bar to establish coefficients, and operational procedures for post-mould cooling devices.

(c) Tundish temperature survey.

(d) Analysis of mould-billet friction as a function of extraction parameters.

The present status of these various lines of enquiry may be summarised thus:

1. (a) Under way in Ottawa. No further bar samples required.
   (b) Completed. Experimental cast (on 14 September, 1972) showed that the reduced casting rate necessitated by increasing superheat allowed the tundish temperature to fall to a steady-state level of 2260°F ± 20F° at the mould entrance. Thus without an extra source of heat to the tundish, superheat cannot be considered a controllable variable.

   (c) Water model tests on baffle design to commence in Ottawa.

   (d) Not attempted.

2. (a) Not attempted in a controlled experiment.

   (b) Not attempted.

   (c) To be examined on the water model.

3. (a) Mould/cooler being prepared in Ottawa.

   (b) No action.

   (c) Details of commercial probe available.

   (d) Load cell(s) and recording unit available. Water-cooled reaction bar required.

Immediate Recommendations

1. Ladle pre-heat to be increased by 200-300°C by using burner cover and/or oil burner.
2. All transfer ladles to be converted to tea-pot type.
3. Discard present wooden slag rakes and install slagging pot, slagger's platform and steel rakes shaped to skim a cylindrical vessel.
4. Examine ladle inoculation in production runs.
5. Install Tec-tip monitoring at casting machine.
6. Install SiC tundish pyrometer and temperature recorder.
7. Install stroke counter and flaw detection station.
8. Install improved rolls ON timer calibrated to stroke length and bar size.
9. Install dwell time monitor in order to control ladle additions.
10. Design and install water-cooled stress reaction bar between holding furnace and rolls stand.

APPENDIX 2

These ten recommendations were discussed, with the following outcome:

No. 1 Agreed - Ladle preheat and melt superheat to be increased.

No. 2 Agreed - After increased preheat/superheat; one teapot ladle will be tried initially.

No. 3 Modified - Close attention is to be paid to deslagging; however, wooden slag-rakes are preferred.

No. 4 Agreed - R. Goller is exploring two approaches:
a) Combine inoculation with Mg treatment at melt furnace,
b) Inoculate by plunging prior to holding furnace.

No. 5 Modified - Present recorder is considered adequate.
No. 6 Agreed - Available equipment inadequate - new unit to be purchased.

No. 7 and 8 Modified - Agreed that purchase of required attachments for above unit could be delayed pending the results of a new program (see after item 10).

No. 9 Modified - Agreed in principle - Foreman to co-ordinate pouring/drawing operation. If results are good, mechanical controls will be installed.

No. 10 Agreed - Dr. Thomson presently has a suitable load cell, and monitor.

Relationship of Turbulence to Flaws

R. Goller proposed a program which would be aimed at varying metal turbulence in the mold by known degrees and evaluating the resulting bar surface. Program outline is as follows:

A) Tests will be conducted during production runs.
B) Controlled variables will be stroke length and baffle position (clearance).

C) Bars in the categories of small (2"-4.8"), medium (6"-9"), and large (10"-12") will be run, twice, under the following conditions:

	Stroke length	Baffle clearance
Small	2", 4", 6"	20%, 40%, 60%
Medium	1.73", 3.5", 5.25"	20%, 40%, 60%
Large	1.5", 3.0", 4.5"	20%, 40%, 60%

D) A total of 54 runs will be required.

E) Baffle clearances will be carefully measured and entered on applicable production sheets.

For further experimentation, two runs will be made (2.3" diameter) with no baffle and long dies. R. Siscoe to order 3" x 13" long dies.

APPENDIX 3

From P.M.D.

(a) Metallography

It was agreed that my present efforts aimed at providing some insight into the mechanism of flaw formation be continued, while on your side, your time and energies would be more usefully applied to the plant development programme involving aspects shown under the headings appearing below. There will of course be occasions when you are required to examine samples yourselves and to facilitate this, I have drawn up and enclosed a suggested sampling procedure which should enable you to more fully relate the section on the microscope to its co-ordinates in the bar from which it was drawn.

From examination of a number of flaws, it appears that the leading edge of the flaw, i.e., that coincident with the lap mark, gives rise to a "crack" running into the bar in the direction of casting. Behind this, and underneath the flaw surface, there are other discontinuities with less well-defined paths, but generally parallel to the first. It can be shown that these groups of discontinuities result from a process of repeated intrusion of thin sheets of liquid and their subsequent solidification one atop the other. At the trailing edge of the flaw, there is usually a small "crack" running in the opposite direction to that of bar withdrawal. Occasionally this trailing discontinuity reaches the same proportions as the leading crack, a fact which may be used to account for your observation of bi-directional cracking in flawed areas. From these and numerous other pointers, I believe it will be possible to fully justify the hypothesis that flaws originate at colder zones of the mould surface and are associated with the assymetry of cyclic ingot shell fracture that results from localised thickening of the ingot shell. This would itself suggest that my original idea of increasing mould wall temperatures in the zone of initial solidification should be re-phrased to read "in certain zones of the area of initial solidification". That is to say we should perhaps be aiming at eliminating the unevenness of radial heat flow at the tundish end of the mould. The interesting question is whether such local differences may be due entirely to quiescent liquid behind the baffle, or whether the assymetry is a more or less uncontrollable characteristic of the mould/cooler assembly, and produces effects which are merely exaggerated by quiescent liquid in the mould cavity.

(b) Baffle Design and Stroke Length

It follows from the above that by varying baffle design and stroke length, one may increase liquid turbulence in the mould cavity and therefore minimise local discrepancies in solidification rate, and you are to be congratulated on so quickly instituting a continuous development programme aimed at relating these casting parameters to flaw incidence. It is a pity that it has had to be interrupted for the mundane business of production, and I hope that the duplicate runs can be re-commenced before too long, i.e., before we have all forgotten what the first series was about. In the meantime I would like to offer the following points for your consideration.

(a) The first concerns the technique of monitoring flaw incidence during a cast. As was pointed out, it is highly probable that the severe-looking black flaws evident on the red bar are in fact very shallow discontinuities, whereas those flaws of a greyish tone bounded by a trailing black edge contain cracks which run quite steeply into the bar. It should be interesting, if you have not already done so, to mark and sample a couple of each type to establish that blackness and crack severity are inversely related.

(b) Partly because of the suggestion that variations in heat transfer originating in the mould/cooler assembly may contribute to flaw creation, it will be important to establish the contribution of that aspect by running say ten identical casts and assessing the variance of flaw incidence between them. This will serve to put into perspective the results obtained by smaller replicate runs in which baffle design or stroke length vary.

(c) From tests on the water model, it appeared that decreasing the area below the baffle had only a slight effect in increasing turbulence on the mould periphery up behind the baffle plate. Similarly, increasing the stroke length at a fixed baffle dimension produced increased turbulence in the lower and central parts of the mould cavity but scarcely affected that region corresponding to the peripheral zone of initial solidification behind the baffle. At this point, I am in danger of trying to anticipate the results of your duplicate series, so argue me down by all means. At any rate, I think that in order to counteract flaw development, it will be necessary to directly apply liquid turbulence to the mould periphery, e.g., by slotting the baffle plate around the mould circumference. I would attempt to explain your preliminary results, which, as I remember them, showed decreasing flaw incidence with increase in stroke length, as follows:- increase in liquid flow rate with smaller mould orifices or longer strokes does not affect localised thickening of the ingot skin. However with the increase in the dwell time of liquid in the mould cavity inherent in using longer stroke lengths, differences in solidification rates become less significant, so that the fracture path at the onset of each withdrawal maintains a symmetry which precludes the development of localised hillocks of frozen shell in the zone of intimate mould/billet contact. It follows from this that any steps taken to increase the average solidification rate, e.g., increasing the heat transfer efficiency of the mould, would also decrease the effect of local discrepancies by again increasing the average shell thickness existing prior to an extraction stroke. It may be of use to you in considering these thoughts to note the relation $d = 0.25\ t^{\frac{1}{2}}$ where d is shell thickness in cm and t dwell time in seconds.

(c) Liquid Handling

The adoption of pouring during a withdrawal dwell time is obviously producing many advantages and might well be automated by overriding the cycling controls with a bell or horn system so that actual visual communication between the operator and the ladlemen is not necessary.

It was agreed that Tec-tip monitoring from the ladle had provided enough basic data on the iron grade at that point, and that similar monitoring should be practised on the metal in the holding furnace to establish a liquidus arrest temperature of inoculated metal. This practice might be increasingly useful as your range of iron compositions increase, i.e., you may be able to identify the degree of superheat associated with acceptable cast quality.

There is one aspect of ladle handling that should be mentioned and that is the present acceptance of heavy slag/metal skulls in the ladle. As part of the general trend of improved practice, I would recommend that you introduce oxygen lancing as a shop floor tool for cleaning both ladles and holding furnace. If you hear that it has been tried and did not work, then reply that it could not have been used properly. The people at Contrecoeur can refer you to Airco or some gas supplier for advice on lancing equipment and technique. Such a skill may be invaluable when you start using tea-pot ladles.

You mentioned that the present recorder was being re-fitted for application to tundish measurement. It would be useful to have its lower scale limit low enough to indicate holding furnace pre-heat. Some comment was made regarding the consistency of thermocouple construction and the apparently low liquid temperatures being recorded. Perhaps the simplest way of arriving at a final practice would be to use the baffle plate as a T/C holder and place a sheathed bead say one inch below the edge of the baffle. The resultant true liquid temperature could then be related to the results obtained from different arrangements of bottom pyrometer.

(d) Sampling of Continuous Cast Bar

Perhaps the major problem in extracting a known 6 oz of metal from 6 tons of bar is that of exercising proper control over the various stages. This is particularly so when production people are asked to provide samples for control or research personnel to work on, and for this reason, sampling should be divided into two distinct stages:-

(1) Macro-sampling

Involving only traverse cuts in the product to produce a log of metal containing the required sample plus enough for a duplicate should this be required. The sample log should be identified with

_______ Run number

_______ Position number

_______ Casting direction

which information should be recorded in a sample register kept by the production unit. No dates or names on the sample should be necessary. Besides putting the three identifying items on the bar surface, these should be repeated on the transverse face which first appears out of the mould. Using this criterion, a double-check of casting direction is always available. Suggested macro-sampling techniques are shown in Figure 1. The macro-sample, simply a section of the cast containing enough material for two samples, or containing some feature in its actual environment, should then be shipped to the interested party. This system has two advantages, viz., the production unit is concerned only with identity and transverse sawing, and the control or research people get a chance to look at the actual concast bar containing their sample.

(2) Micro-sampling

Refers not to microscopy, but to the extraction of the test pieces required, be they longitudinal or transverse tensiles, microscopy specimens, hardness survey blanks, etc. Control of this procedure is best achieved by painstaking note-taking and diagrammatic illustration. It is essential that the entire log be marked before machining so that not only the extracted sample is properly identified by the three parameters, but so also is the remainder of the macro-sample. This precaution will facilitate returning to the macro-sample for a duplicate test piece or further exploration. As with macro-sampling, a double-check on continuous casting direction is readily made by placing the identity marks on the first transverse face to leave the mould, or, if that is impractical, simply marking the letter F on that face. Identity marks on surfaces parallel to the casting direction should always read left to right when the casting direction is left to right as viewed from the operators' control console.

There are a number of suggestions that might be made with respect to the different objects of micro-sampling. In the case of surface defects, e.g., flaws, metallographic samples are generally taken on a longitudinal plane. The characteristics of the flaw will appear to vary with respect to casting direction unless some care is taken to polish the proper longitudinal face. A scheme for sampling for flaws is shown in Figure 1 and results in micro-samples which, irrespective of flaw position on the bar, have a common casting direction as viewed. Lucite is to be preferred as a metallographic mounting medium since it enables one to relate the cast surface with the sub-surface, and allows a double-check of the identity of the marked and mounted sample.

Where quality control procedures call for an assessment of porosity, inverse chilling, or hardness surveys across a diameter it should be noted that longitudinal sections are much more informative than the more easily obtained transverse slice. This generally accepted axiom is especially applicable to con-casting using intermittent withdrawal. For example, long stroke lengths may result in cyclic areas of chilling or porosity in the last portion of the bar to freeze. A true evaluation of the overall importance of these defects can only be made by longitudinal sectioning. The same type of comment applies to sectioning for slag inclusions which tend to congregate near the 12 o'clock radius on the bar. The transverse slice has a very limited usefulness in quality control, and may only be accepted as a control sample when it has been shown that bar characteristics across the section do not vary through the distance of one stroke length.

APPENDIX 4

From P.M.D.

Mould Lubrication

I am strongly tempted to comment on the possible application of lubrication to a graphitic mould system of the closed-head type, or indeed to any closed-head mould assembly. The starting point for such a topic is a consideration of the function of lubrication in the simplest casting unit, i.e., an open-head stationary mould from which the casting is continuously withdrawn. If the level of mould/billet friction opposing the withdrawal load exceeds the rupture load of the freezing shell, then progressive shell fractures will occur at lower and lower levels in the mould until a break-out occurs at the mould exit.

It is necessary, therefore, to minimise mould/billet friction by applying lubricant to the mould wall and so form an interface between the surface of the solidifying billet and the mould. When this simple open-head casting system, utilising continuous withdrawal, is converted to a closed-head system, it has been found necessary to retain a small liquid meniscus at the junction of the mould and liquid reservoir in order to provide an area of free mould surface through which lubricant may be applied to the region of initial solidification. There are two minor variations of the necessity of providing continuous lubrication when using continuous withdrawal. In the first, in which the total length to be cast is of the order of 8-15 ft, it is sufficient to pre-coat the mould wall with lubricant prior to casting. The secret here is that all of the metal should be cast before the lubricant on the wall is used up. Such "once only" lubrication for short lengths of batch castings is used in both open- and closed-head metal and graphite mould units. The second variation is that of the continuous pressurised application of oil through a porous graphitic mould (e.g., the Apex process).

In cases where the use of lubricant in continuous withdrawal from stationary moulds may not entirely eliminate high mould/billet interfacial frictional loads, the possibility of successive shell fractures reaching the mould exit may be precluded by introducing a "rest" period of zero frictional loads. During this dwell period the relative velocity between the mould and billet is zero, and the continuing solidification of metal in the mould heals the fractured ingot skin (under zero tensile load) to re-establish the liquid/solid profile which existed just before fracture. The dwell period is, of course, produced by

a) reciprocating the mould so that its forward stroke occurs at the same speed as that of continuous withdrawal of the casting

or b) intermittently extracting the casting.

Examples of these alternatives are to be found in:-

I Metal moulds - Open head reciprocating - steel
II " " - Closed head " - Tessman process
III Graphite moulds - Open head reciprocating - Copper
IV " " - Closed head " - Russian practice
V Metal mould - Open head intermittent extr. - Babcock steel
VI " " - Closed head " " - Davy Ashmore
VII Graphite mould - Open head " " - ?
VIII " " - Closed heat " " - Cast iron, etc.

Lubrication is common in groups I, II, III, and V, and is not known to be practised in the others. It is at this juncture that the perspective I am trying to construct loses some of its definition because one cannot apparently say that all metal mould systems use lubricants and graphite types do not, nor can one say that open-head units employ lubrication and closed-head units do not. Similarly, one cannot relate lubrication specifically to either reciprocation or intermittent withdrawal practices. In an attempt to reduce these complexities to some degree of order, may I offer the following points of argument?

1. Where the mould/billet relative velocity is constant, e.g., stationary mould and continuous withdrawal, lubrication is essential to avoid shell fracture and a resultant breakout at the mould exit.
2. Where this relative velocity decreases cyclically to zero, as in intermittent withdrawal or reciprocation, shell fracture may occur without leading to a breakout since the point of fracture is cyclically contained at a certain level in the mould.

3. Since an oscillating relative mould/billet velocity controls shell fracture, there is no need of lubrication from the point of view of eliminating successive fractures and eventual sub-mould breakout.

4. When both reciprocation or intermittent withdrawal and lubrication are used, the latter may fulfill one or both of the following objectives:-

   (a) the lubricant may reduce mould/billet frictional levels below the fracture strength of the shell so that the entire skin moves intermittently down the mould wall. In this case, the dwell period of zero relative velocity acts as a safeguard against any fractures which may occur due to lubricant failure at any point on the mould wall. Surface quality will be enhanced since the severity of lap or wash marks at the tip of the undamaged shell will be much less severe than those occurring at a fracture edge on the lower part of the shell.

   (b) Even if it does not prevent shell fracture, the presence of an interfacial lubricant phase between the mould wall and the surface of the casting reduces the adhesion of the casting to the mould and effectively transfers the area of maximum mechanical interaction to a region close to the line of initial solidification. The healing of cyclic fractures of the thin-walled ingot in this zone requires less time, and thereby permits faster casting rates than would be possible if the fracture site were further down the mould; and again, the reduction in lap or wash mark severity enhances surface quality.

These points may be summarised by saying that although no lubrication is essential in systems using reciprocating moulds or intermittent withdrawal, its use may improve surface quality and increase operational casting rates.

5. The design characteristics of the mould system affect the type and method of application of a lubricant. Provided the mould wall temperature in the area of initial solidification does not exceed the boiling point or flash point of the oil or grease used, these may be applied continuously or batch-wise to open or closed systems. Thus, we find that both metal moulds and directly spray-cooled graphite moulds may have lubricant applied to them.

6. Lubricants for use at higher mould wall temperatures (e.g. >600°C) may be found in various MO-SiO_2 compositions. Examples of this type, though common in extrusion processes, are rare in continuous casting. Indeed, only one example exists, viz., the use of artificial silaceous slags in the strand-casting of steel using reciprocating moulds. In this particular case, the lubricity of the oxide phase is of minor importance compared to its insulation and scavenging action. Interestingly enough, although strand-casting in general uses copper moulds to keep mould wall temperatures below the flash-point of rape seed oil, when the latter was supplanted by artificial slags in some applications, the copper moulds were retained. It could be argued that better surface qualities might be realised by using other mould materials in place of copper, viz., those which might incur higher mould wall temperatures when slags are used as a cover-cum-lubricant. I mention this merely to illustrate that the use of high temperature glassy lubricants is at present very little understood, and never discussed analytically in the available literature.

7. Water-jacketed graphite moulds experience very high temperatures on the inner mould surface. The normal lubricants such as oils and greases are, therefore,

inapplicable. If the mould reciprocated about a nozzle, as in the Tessman process, then it would conceivably be possible to coat the exposed mould surface with a glassy lubricant in much the same way as Tessman uses oil. However, if intermittent withdrawal from a stationary mould is used, I don't see how you could supply a molten slag to the peripheral zone of initial solidification.

8. One of the major problems in strand-casting practice using artificial slag covers is artificial slag inclusions in the cast billet. In the light of this, and from a common-sense point of view, it does not seem desirable to introduce a slag phase into the mould cavity of a horizontal casting unit.

9. Graphite itself has a low coefficient of friction in contact with solids, although whether this lubricating quality persists at high temperatures is another matter. Possibly the physics literature has something to offer there.

I have, at least I think I have, argued to a point at which one can say it is just not possible to lubricate, by any means, a horizontal unit of the type you are presently running. If one admits the possibility of design alterations to include a lubrication parameter then there are two choices open:-

a) A high temperature glass lubricant - not acceptable on the grounds of consequent inclusions in the product

b) Lower the graphite mould temperature by more direct cooling and admit oil through capillaries or the intergranular pores of the material. Alternatively, one might go to a metal mould unit of the Davy Ashmore type. It is not known whether the latter actually uses lubrication or not. I suspect not. In any case, lowering the mould wall temperature to maintain an oil boundary layer automatically increases the freezing rate, a step which is probably not as acceptable with cast iron as with other alloys. Increasing the heat extraction rate in the mould would mean increasing casting speed in order to retain an acceptable surface quality. Increasing sump depths would result, and feeding the horizontal solidifying core would become the major problem.

Since neither (a) or (b) are acceptable in theory, we are back at the proverbial square number one. It seems to be a suspiciously fortuitous state of affairs, but I must conclude that the basics of your present casting machine are the only ones applicable to the product, and do not allow the admission of a lubrication parameter. That is not to say that cast surface quality must be accepted as an uncontrolled variable built into the process by Herr Krall. Since surface quality is dictated by the characteristics of the zone of strong mechanical interaction between the solidifying shell and the mould wall, and since these characteristics in turn control the presence or absence of shell fracture, and the symmetry and position of shell fracture paths, it may be argued that one might beneficially influence surface quality by introducing changes which limit the degree of mechanical adhesion of the shell, and move the shell fracture path as close to the peripheral ring of initial solidification as possible. I personally cannot accept that it would ever be possible to intermittently withdraw the entire shell of cast iron from the present mould system, i.e., adhesion, and therefore cyclic shell fracture, are unavoidable when one considers

(a) the initially frozen ring of solid does not try to contract against the ferrostatic liquid pressure acting against it as is normally the case in continuous casting. The volume expansion associated with graphite precipitation in cast iron will increase the mould/billet interaction normally found at the tip of an ingot shell.

(b) that, bearing in mind the temperatures and mechanical pressures involved in the area of initial solidification, and the identity of the two solids, viz., C and Fe, there may well be a chemical bonding taking place at points of intimate contact. Such "pressure welding" at the interface may contribute significantly to total mould/billet adhesion.

Taking the last point first, one might talk vaguely about SiN, SiC, BN mould materials, all of which are too expensive to be used to produce material worth cents per lb. In a more positive vein, I believe that higher degrees of surface finish in the upper reaches of the mould may lessen the degree of adhesion and thus facilitate fracture at a level closer to the line of initial solidification.

Another design variable which may be significant, and one I would like to see you try is that of machining a negative taper on the tundish end of the mould, that is to say the mould i.d. increases in the direction of casting. For example, taking the tundish end of a 9" mould as a reference line, the inside diameter might be A in. at the start and increase by 0.008" per in. for 4 in., being parallel sided at A + 0.040" i.d. for the remaining 5 in. of mould length. This may decrease the extent of mould/billet mechanical interaction and push the cyclic fracture site toward the tip of the ingot shell. I have in fact used such a negative taper to avoid bar fracture in casting small sections of cast iron containing the vermicular graphite, i.e., a grade known for its volume expansion on freezing.

APPENDIX 5

Selection of Test Conditions for Experimental Casts

1. Pouring Temperature

   This temperature will be maintained within the limits determined by previous experiments. The pouring temperatures are shown on the attached graph, Figure 5.

2. Dwell Time

Dwell time, which determines the casting speed, is based on an equation for the length of the liquid metal sump in the bar. In this test, in order to reduce the number of experiments, casting speed for various bar sizes is considered constant given that the sump apex angle is constant. The equation for the sump length reads as follows:

$$l_s = kvD^2 - C$$

where k is a constant equaling 0.27 in. v is casting speed (in/min) D is bar diameter (in) and c is a constant corresponding to approximately 10% of l_s. This constant is neglected for this test. From the sump length the apex angle can be calculated for a given bar size and casting speed. In the attached diagrams the casting speed and dwell time per 1 inch stroke length is depicted for apex angles 2°, 4°40' and 6" for every size of bar produced. The red line illustrates the maximum casting speeds which are being used in the present operation.

For this test, at least three dwell times will be selected (three apex angles) for each group of bar sizes. Each selection represents one heat.

Essentially stroke length, casting speed and bar size will be varied independently whereas baffle position will be constant, die wall thickness will correspond to dies which are now available and metal temperature as well as C.E. will be based on previous operating experience. With the three variables varied at three levels, 27 heats are anticipated to fullfil the requirements of this project.

Each heat will be assessed as for crack incidence by the technique used in the preliminary test.

3. Bar Size
For test purposes our range of bar sizes is broken down in the following fashion: small sizes - below 4 in., medium sizes 4-10 in. and large sizes above 10 in.

4. Stroke Length
According to previous test results long strokes are preferable. Thus the stroke lengths will be selected within the range of 4-8 in. Three lengths will be tested in each bar size group.

5. Die Wall Thickness and Bar Temperature
Both the thickness and temperature will be recorded.

6. Liquidus Temperature
This temperature will be approximated from carbon equivalent as determined by the control lab and from the attached diagram.

7. Bar temperature should not exceed 1910°F in small sizes, 1880°F in medium sizes, and 1840°F in large sizes.

Assessment of the Test

The following table will be filled out for every heat:

Date	Bar Size	Cooler Type	Die Thickness in.	Baffle Clearance %	Ladle No.	Pouring Temp. °F	Stroke Length in.
		New or Old					

Dwell Time Sec.	Bar Length in.	Bar Temp. °F	Crack Incidence ft^{-1}	C.E. %	Liquidus Temp. °F	Casting Speed in/min.

The stroke length and dwell time will be taken from the end of each ladle. An eventual correction will be taken by measuring the length of bar produced per ladle and by determining the average casting speed within the ladle.

Each ladle will be considered as a distinct unit and will be represented by a complete set of values which will be assessed by means of regression analysis.

APPENDIX 6

From P.M.D.

Perhaps my main comment has to be a re-statement of the criticism made of the truncated preliminary test, viz., the absence of replication at any fixed levels of factors, and the corresponding absence of any indicator as to the degree of control achieved one run to another. It has been said on many an occasion that flaws may be present one day and absent the next, with no changes in practice consciously made. Acknowledging that this may be true to some degree, it is essential that the weight of such hidden sources of error in interpretation be estimated in any experiment designed to yield statistically derived conclusions. It should not be difficult perhaps to locate at least one or two of the larger orders scheduled >30,000 lb and run replicates with fixed treatment combinations of stroke length, dwell time, etc., etc., in order to obtain a measure of batch to batch variance. It should then be possible to impose this Expected Mean Square on the Anova of your intended 3^3 factorial experiment to determine if there is any biased component in the residual error term produced by analysis of variance.

Before discussing the selection of test conditions, I would like to comment or rather, ask, about the technique of establishing a crack incidence figure. You may remember we decided that the hypothesis that deep cracks were black and shallow cracks grey was probably reversed, and should be checked by sampling the two extremes. This was the original intention of utilising color stills of the bars leaving the mould. If this has not been done, will you use total flaw densities, irrespective of type, or continue to differentiate as in the preliminary test? Still on the observational aspect, would it be possible to have a man follow through each cast to the machine shop and establish, for the duration of these tests,

a) the number of flaws in the black bar of each cast. This should provide a second estimate of total crack incidence for each cast.

b) the number of surface cracks after machining to size, and

c) after re-machining if this is practised.

The object here would be to attempt to cover the possibility that casting conditions producing a relatively high density of easily removable shallow cracks may be more economic in the long run than conditions yielding a lower incidence of deeper cracks. I am not assuming that frequency and depth of cracking are inversely proportional, merely admitting the possibility that this might be the case.

If I may, I would like to comment on test conditions as they are described in your report (5-73).

1. Pouring temperature is given as a function of bar size in Figure 5 and the liquidus temperatures are shown in Figure 6. Since you are forced to draw on different compositions for the 3^3 experiment, you will use various degrees of superheat if Figure 5 is followed explicitly. Therefore, superheat becomes a variable in a regression analysis. This is probably a thin argument since the temperature of metal admitted to the mould seems to settle down to 2240 ± 10°F irrespective of initial pouring temperature. Even then, this will incur various degrees of superheat depending on the liquidus.

2. Dwell time was wholly confounded with stroke length in the preliminary test and it is good to see it extracted as independent variable. However, I am a little hesitant about endorsing the arguments used to normalise variations in casting rate and bar size using the concept of sump apex angle, and for the following reasons:

(a) as you well know, the sump tip is not the apex of an isosceles triangle so that

$$\mathrm{ta}\ \alpha \neq \frac{D}{2\ell}$$

(b) we are concerned, not with the length (or symmetry) of the sump, but with mould events, the factors affecting them, and particularly with the region of initial solidification. It is important then to normalise v with D from the standpoint of solidification within the mould, rather than in the post-mould region.

Now this last approach produces precisely the same result as the one you have used, so you are free to accuse me of academic quibbling as regards the reasoning procedures.

Mine rely on the observation (Klein Giesserei Tech-Wiss. Beihefte 1953 (10) 441) that the temperature distribution in continuous cast ingots will be geometrically similar provided their casting speeds are in inverse proportion to their diameters, i.e.,

$$vD = \text{constant}$$

Your casting practice quite closely obeys this relationship giving

$$vD = 85\ \text{in}^2\ \text{min}^{-1}$$

so that if we wish to vary the geometry of temperature distribution in the mould in a controlled way, we simply choose new values of vD and evaluate the required dwell time per inch of stroke length for each value of D and vD. Since vD=85 in^2 min^1 represents a maximum operating rate, one might vary dwell time by choosing lower values of vD, e.g.,

Level	vD	D = 5 in.	
		v	Dwell/in stroke
A	85	17	3.5
B	75	15	4.0
C	65	13	4.6

Equivalent dwell times/inch can be calculated for all bar sizes. Since you are stuck with production runs, the lowest level of vD that can be investigated will be limited by white iron solidification (cold mould wall) at lower casting rates. As you can see, electing values of vD gives the same result as casting to a constant "apex angle", but does not involve the approximation of symmetry or the small possibility of identifying your sump triangle with a solidification profile, which it is not.

I am most interested in this particular aspect of your programme, because, as I mentioned, the previous use of longer stroke lengths automatically involved longer dwell times, and so their effects on crack incidence could not be separated. Since increased dwell time, and therefore lower casting rate, should decrease the extent of interfacial interaction between mould and casting, it may serve to rectify the variations in crack path which we associate with flaw creation.

3. Bar size breakdown - no comment.

4. Stroke length is another argumentative subject from two points of view, the first of which is that in choosing a range of relatively long stroke lengths you may severely limit the distribution of crack incidence over all casts and so render any analysis of factorial effects difficult.

I would prefer to see the range stretched downward into known conditions of relatively high flaw incidence, so that the effects of stroke length, etc., are readily detectable. There must be a neat mathematical way of putting this, but it is beyond me.

The second point is a more obscure one and concerns the interaction between bar size and stroke length. If we assume that a reduction in crack incidence at longer stroke lengths is due to increased turbulence in the mould, and not to the previously simultaneous increase in dwell time, then we should attempt to normalise this turbulence, viz. a viz. bar size, in the same way we propose normalising temperature distribution using vD = constant levels. That is to say the effect of stroke length per se can be identified only if we vary not absolute stroke length, but the ratio bar diameter÷stroke length. This arises because the velocity of liquid entering the mould is the same for all conditions (5 X the peripheral roll speed) and its area is the same proportion of the mould cavity (20%), so the amount of stirring action it can create is proportional to the length of the moving segment-column of liquid. For example, a 4-inch stroke length will not agitate the liquid in the upper part of the mould cavity as much in a 12-in. diameter mould as it would in a 6-in. diameter mould. The importance of turbulence, and the necessity of exceeding minimum values of stroke length/diameter ratios in order to generate it and so avoid surface defects, have been described before (by me, naturally!).

Choosing ratios is relatively easy, but applying them may be difficult. A ratio of 1 may produce relatively flaw-free 8-in. diameter bar, but would give the lowest crack index possible with 10-in. diameter bar. This may be the strongest case yet for longer moulds.

The best one could do is use low, medium and high levels of L/D, and let the computer sort it out. It is worth noting that from the data on flaws drawn up by Allan Bailey for bars cast with 2 - 2 1/4-in. stroke length, the rejection rate increased rapidly at $L/D < .75$. In any event, whether this ratio concept is used before or after the tests, may I repeat my suggestion to use stroke length ranges which will definitely produce some readily estimable flow density.

5. Die wall thickness is clearly significant at start-up in large bar sizes in terms of the initial heat sink effect, but accounts for a relatively minor proportion of the temperature drop between the cast surface and the cooling water (4-8%). There is one point though on graphite mould geometry that I would like to bring up and again it is concerned with the changing shape factor in the operation as bar diameter increases. Flaws are generated at the zone of initial solidification, which in smaller bars, is a measurably finite distance from the baffle plate. There is some evidence that, with a constant mould length, this zone approaches the baffle plate closely at larger bar sizes, and one is forced to raise the point should not the protruding length of mould increase with bar diameter?

With respect to the two designs of cooler, I would imagine both have been used over the complete size range and, therefore, both contribute to the observed $vD = 85$ in.^{2} min^{-1}, limiting bar temperatures, etc. It should suffice, therefore, to allow the analysis to decide whether there are more flaws from one rather than the other.

To summarise then, my comments amount to

(a) following up crack incidence on the hot bar with inspection of un-machined and machined bar

(b) evaluating 3 levels dwell time per in. of stroke length by setting vD = 85, 75 and 65 $\text{in.}^2\ \text{min}^{-1}$

(c) rather than selecting 3 levels of stroke length, independent of bar size, from the range 4-8 in., choose three levels of stroke length per bar size such that some attempt is made to hold three levels of stroke/diameter ratio constant over the series. The lowest of these ratios should be one expected to generate flaws. You will note that (a) and (c) merely expand your proposal and (b) is simply a different way of looking at casting rates.

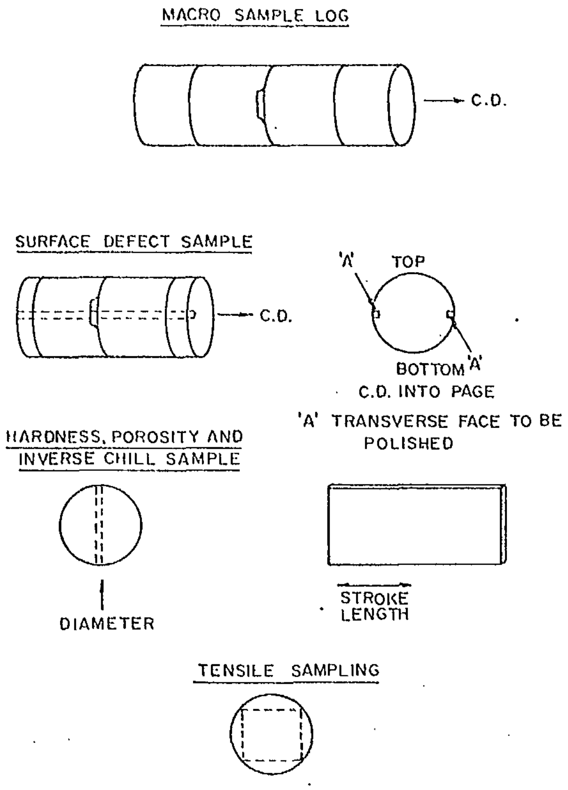


Figure A1. Proposed sampling scheme for defect analysis and metallurgical control.