SEGREGATION AND INTERNAL WEAKNESS IN FORGING INGOTS

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SOME of the types of segregation which occur in ingots (FIG. 1) may be avoided if the necessary precautions are taken, this is true with regard to blowhole segregation, corner segregation and 'V' segregation; nevertheless, such types of segregation are still by no means uncommon.

The type of segregation generally known as 'A' segregation which occurs at positions between the ingot axis and the outer surface still remains a baffling problem, no means having so far been found for its prevention.

In addition to the various types of segregation and apart from primary pipe which can be easily dealt with, problems arise with regard to secondary piping, and discontinuities and porosity around the top of the basal cone.

Some recent trials at the works of Steel, Peech and Tozer made in connection with the problem of solidification rates and segregation have served to throw a little further light on the twin problems.

In one trial a 22 in. sq. ingot of 0·63 C steel was inverted 64 min. after casting (FIG. 2). On sectioning it was found that segregated liquor had drained out of the matrix to the depth of about $1\frac{1}{2}$ in. and some of the 'A' segregates had completely drained out. The pool of segregated material was analysed and the degree of segregation was found to be as follows:

TABLE 1

	POSITION A	POSITION C	POSITION D	RATIO D/C
C	0·640	0·460	1·040	2·25
Si	0·127	0·121	0·132	1·10
S	0·036	0·024	0·114	4·75
P	0·022	0·010	0·057	5·70
Mn	0·830	0·790	0·960	1·22

The difference in the analyses between some positions indicates that of the inner $1\frac{1}{2}$ in. of the apparently solidified wall about one-third was still liquid and sufficiently fluid to readily drain out.

The initial freezing point of the steel as cast was 1483°C. calculated according to Roeser and Wensel[1], whereas the initial freezing point of the segregated liquor was 1452°C., i.e. 31°C. lower.

Marburg[2] has pointed out that the bottom end of each of the outer lines of 'A' segregates appears to start at the same distance from the outer wall, and this hypothesis received some support from this ingot (FIG. 2).

A recent study of the 'A' segregates occurring in a Ni-Cr-Mo ingot (40 in. octagon) made by Steel, Peech and Tozer (FIG. 3) provided good evidence that the segregated liquor, lying along the advancing wall of solidification, eventually reaches the stage where its initial freezing point is so far reduced below that of the adjacent liquid steel that solidification occurs on its inner side, so entrapping it. It was seen (FIG. 3) that the dendrites on the inner side were smaller than those on the outer side of the segregate, differently orientated, and that a shrinkage cavity had formed in the segregate showing it to have been cut off from the liquid metal. There is nothing new in such a hypothesis, Brearley[3] having put it forward in 1918.

It certainly appears from Marburg's work[2] and from the evidence of our own trials that

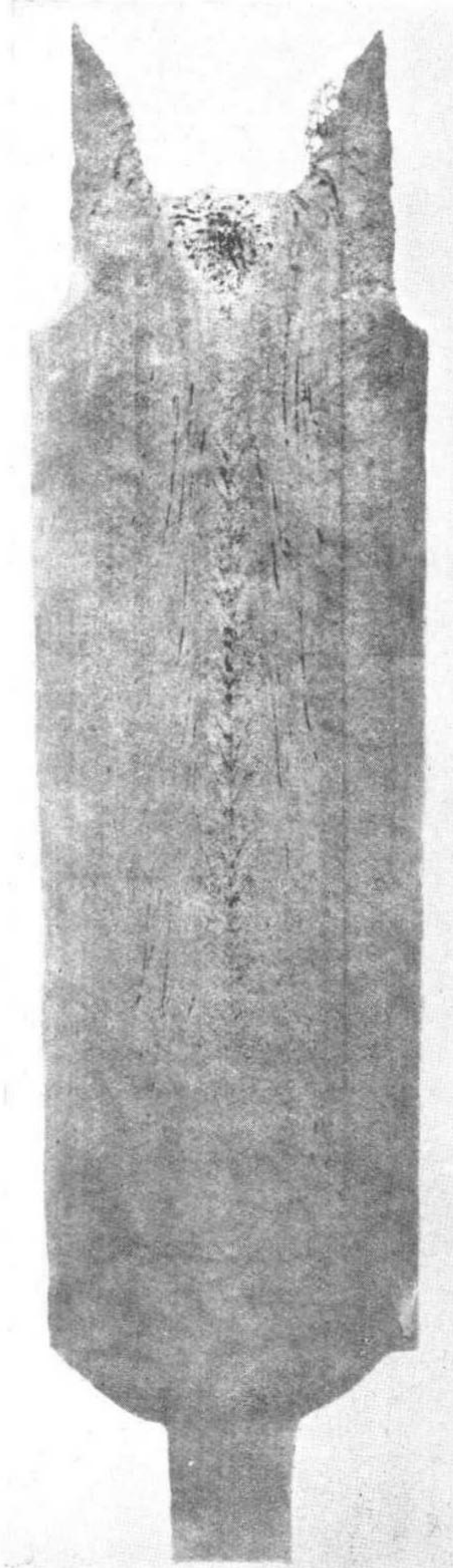


FIG. 1 — SULPHUR PRINT, 40 IN. OCTAGON

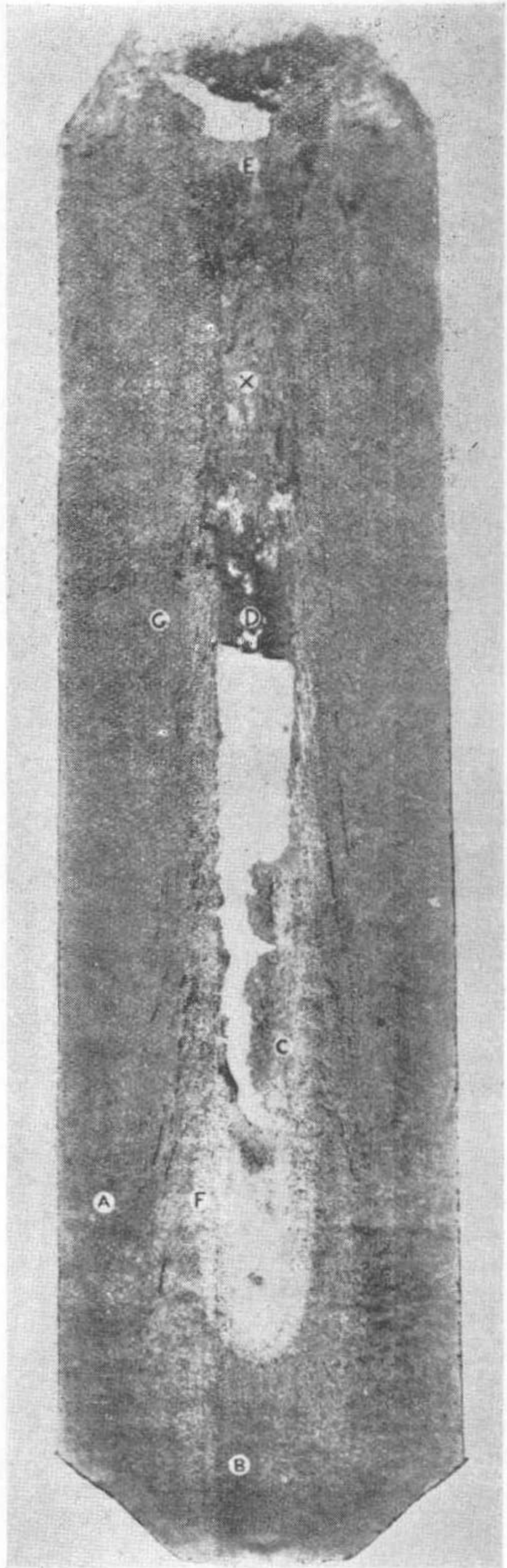


FIG. 2 — SULPHUR PRINT, 22 IN. SQ. INGOT OPENED 64 MIN. AFTER CASTING

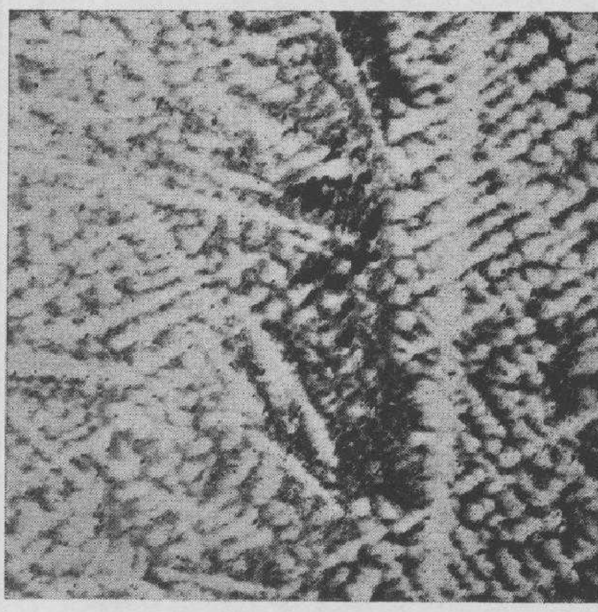


FIG. 3 — 'A' SEGREGATE WITH CONTRACTION CAVITIES. ×5

the advancing wall is carrying forward a highly segregated layer which steadily becomes richer in the chief segregating elements, C, S and P.

Since the advancing wall is of almost uniform thickness from top to bottom of the ingot, why is the entrapped segregate not approximately parallel to the outer surface? An answer which readily occurs to one is that while the advancing wall is approximately of the same thickness throughout its length, the temperature of the liquid metal will be lower towards the bottom end owing to the cooling effect of the bottom plate, the segregate layer will, therefore, be first trapped at the bottom end and at progressively later stages from the bottom up. Fig. 4, which is a reproduction of Fig. 1 of the Report on the Heterogeneity of Steel Ingots[4], appears to lend strong support to such a hypothesis. In a hot top ingot such as this, fairly short in length relative to breadth, the difference in metal temperature between top and bottom is of course accentuated, resulting in a steeper angle of slope of the entrapped segregate. The way the segregate lines spread outward towards the 'hot top' lends additional support, i.e. for a given time the advancing wall of solidification from the refractory head will be less thick than lower down where it is advancing from the mould wall. The segregated layer will, however, probably be of similar composition at both points, i.e. its initial freezing point sufficiently reduced

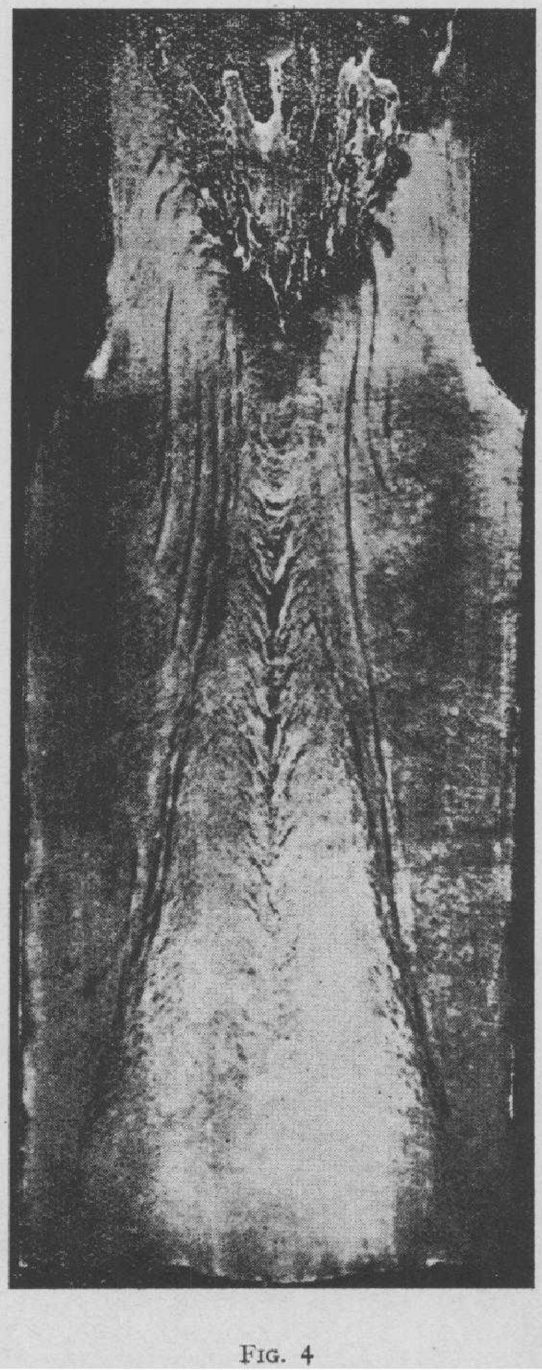


FIG. 4

to allow of preferential freezing upon its inner side. No such curvature of the 'A' segregate occurs in the absence of a 'hot top'.

One might think, on first looking at the segregate pattern of the 10-ton ingot in question (FIG. 4), that the segregate lines were at the junction of the advancing walls of horizontal and vertical solidification, but a moment's thought would dispel such an idea.

The correctness of the hypothesis that the advancing wall of solidification is carrying forward a layer becoming increasingly rich in segregates is supported in other directions than that associated with 'A' segregates. In the case of corner segregation, for example, (FIG. 5) all the evidence available indicates that corner segregation arises from segregated liquor flowing back into a stress crack or internal tear starting on the inner side of the advancing wall of solidification.

Again, in the case of effervescing or rimming steel (FIG. 6): the thickness of the solidified material, at the time effervescence ceases or is brought to a close by the addition of aluminium or by capping in a bottle top mould, can be readily determined by

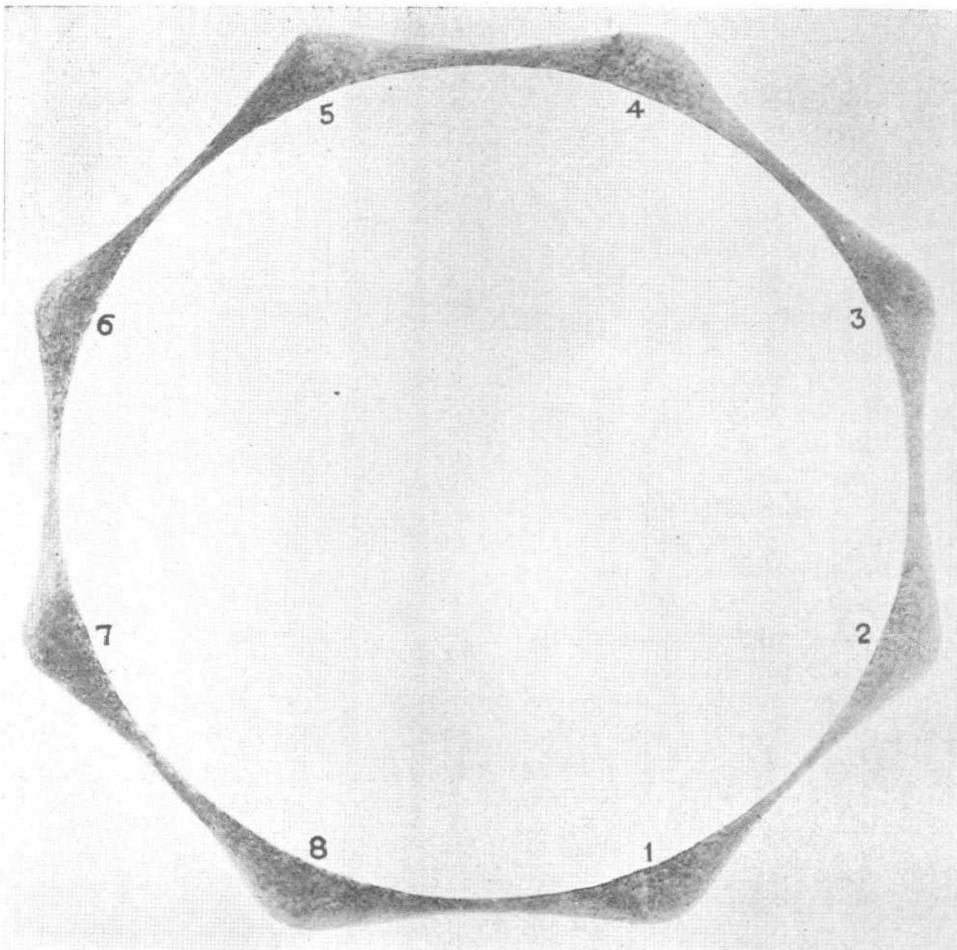


FIG. 5 — SULPHUR PRINT OF RING FROM OUTSIDE OF 26 IN. OCTAGON INGOT

FIG. 6 — BLOWHOLES IN EFFERVESCING STEEL INGOT

reference to the position of the segregated zone at the rim-core interface. Gas which has been freely escaping is suddenly trapped resulting in a series of blowholes on the face of the already frozen metal, i.e. the secondary system of blowholes common to all rimming steel ingots. This zone is always highly segregated, the degree of segregation depending upon the lapse of time before the effervescence or rimming action is stopped.

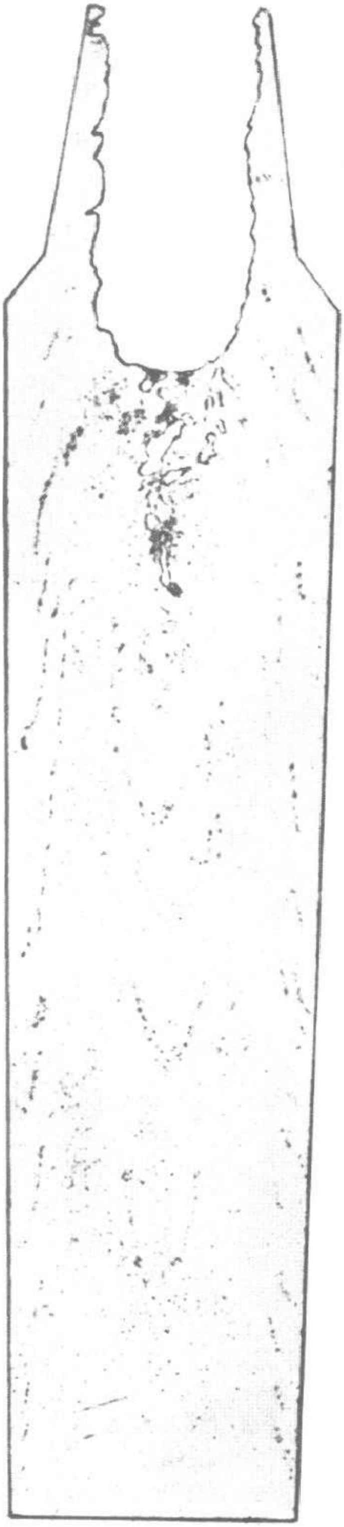
It seems important that the precise mechanism of 'A' segregation should be discovered, for until this is done there is but little hope of its reduction or elimination.

'A' segregation does not normally occur in small ingots, less than 18 in. sq. if cast into chill moulds. If cast in sand, however, 'A' segregation readily occurs (FIG. 7).

Since it is an expensive and laborious business cutting up large ingots in order to study segregation phenomena, and since large ingots only segregate in such a manner owing to the long time taken to solidify, a more rational method of studying the problem would appear to be experimentation with small ingots, 10 in. sq. or so, in which the rate of solidification was automatically controlled to simulate the solidification times taken by ingots 20 in. sq. or larger; some work on these lines has already been done by B.I.S.R.A., but means have not yet been found of controlling the solidification rates sufficiently closely to yield reproducible results.

All that appears to be generally possible at the moment, to reduce the ill-effects of 'A' segregation, is to keep the segregating elements S and P at the absolute minimum; nothing unfortunately can be done about the carbon.

It is also possible, in certain cases, to use ingots of small cross-section, e.g. for railway tyres an ingot of small cross-section, 18 in. or less, yielding a longer block for tyre making might be used in preference to an ingot of larger cross-section. Again, for certain forgings a small cross-section ingot might serve the purpose if the ingot was upended 50 per cent or so as a preliminary forging operation.



Corner Segregation

Corner segregation is a much more serious fault than 'A' segregation, but fortunately the trouble can be overcome, in nearly all cases, by attention to mould design.

Some years ago in certain forgings, corner segregation (FIG. 5) was so prevalent in Ni-Cr-Mo ingots that it became necessary to machine the corners of the octagon ingots until sulphur printing showed that such corner segregation had been removed.

The results obtained on large numbers of octagon ingots led to several interesting conclusions:

(1) It was found that corner segregation, when it occurred, was on one or more adjacent corners, no segregated corners were found with a sound corner in between.

(2) Trials proved that the corner segregation could be avoided if the teeming rate was sufficiently slow, but this remedy led to sand inclusions and so proved worthless.

(3) It was further found that the segregated corners were always on the side of the ingot which had been nearest to its neighbouring ingot during the casting operation, i.e. it was the hottest side as the moulds were arranged in the casting pit. This led to the moulds being spaced further apart so that the heating and cooling were more regular. This led to a marked reduction in the number of segregated corners, but by no means to their complete elimination.

(4) It was further found that the incidence of corner segregation varied with the flute radii of the moulds, i.e. moulds with a larger flute radius, or, in other words, shallower flutes gave most trouble.

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FIG. 7 — 15 CWT. INGOT SULPHUR PRINT

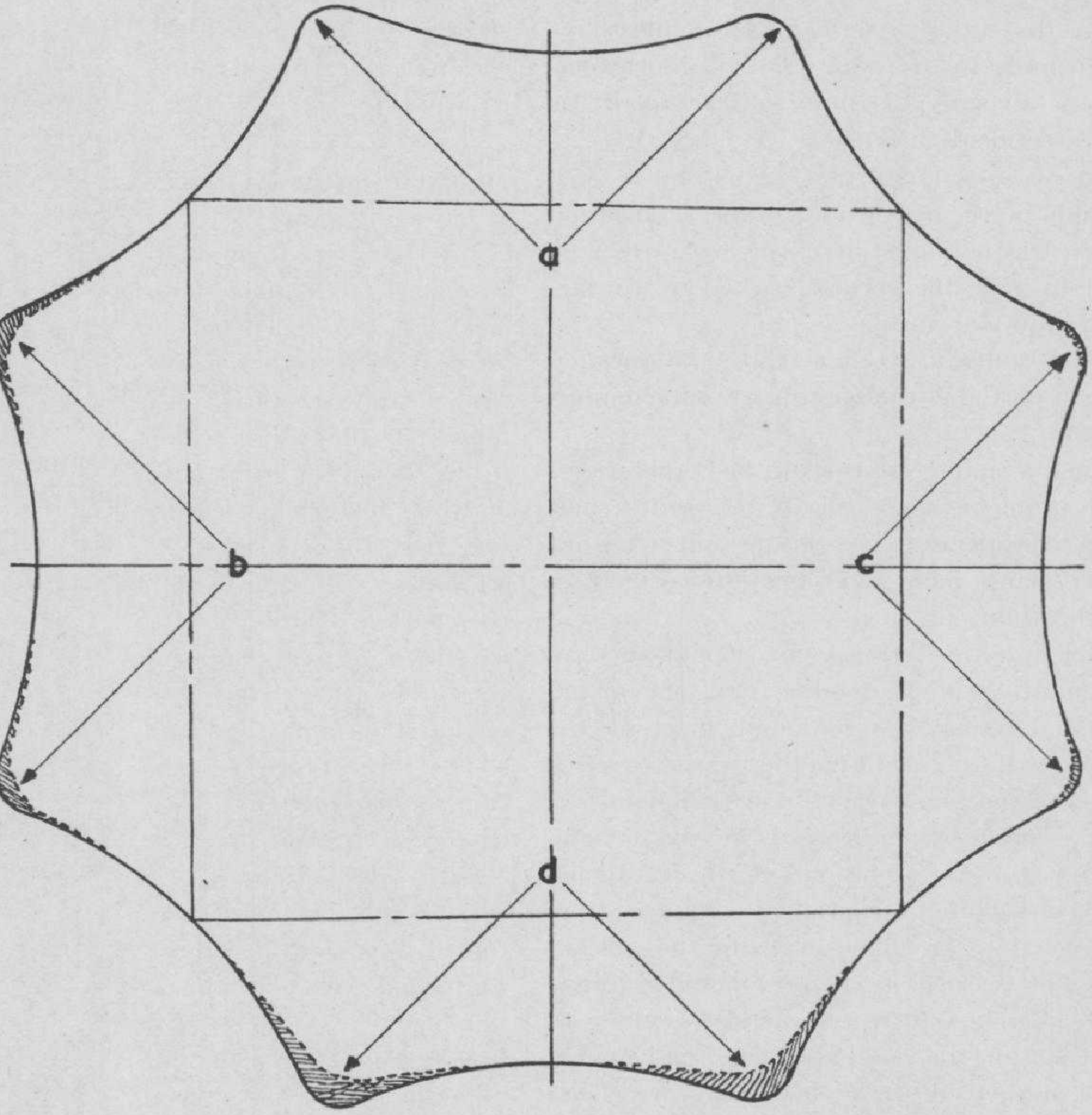

FIG. 8 — SKETCH COMPARING NEW 26 IN. OCTAGON MOULD WITH 24, 26 AND 28 IN. OCTAGON MOULDS. a: Central black outline is the contour of the inside of the new 26 in. octagon mould. b: Black outline indicates 26 in. contour (new), dotted line indicates 26 in. contour (old), hatched portion indicates difference in contour. c: Black outline indicates 26 in. contour (new), dotted line indicates 28 in. contour, hatched portion indicates difference in contour. d: Black outline indicates 26 in. contour (new), dotted line indicates 24 in. contour, hatched portion indicates difference in contour

That this effect was a real one was proved as follows:

One particular mould resulted in about 80 per cent of the ingots cast in it being segregated at one corner or more. The mould was, therefore, modified by deepening the corners by machining. Many ingots were subsequently cast in this modified mould and all were free from corner segregation, as proved by turning and sulphur-printing, although companion ingots of the same casts of steels suffered from the trouble as usual.

On measuring the increased depth of flute of the ingots cast in this modified mould it was found to be equivalent to a 13 in. flute radius, i.e. half the cross dimension of the mould which was 26 in.

All the moulds in use at that time were then measured in a similar manner and the flute radii were found to differ considerably from one size of mould to another (FIG. 8).

Since that time all the octagon moulds have been made to the same relative dimensions, e.g. in all sizes the flute radius is half the cross-sectional dimension.

It was soon found that ingots cast in such moulds were free from corner segregation and it was no longer necessary to let them go cold to have the corners proved by turning and sulphur-printing.

The results of the investigation in question were reported to the appropriate sub-committees of B.I.S.R.A.[5,6]

Such a simple solution to the corner segregate problem was naturally received at first with considerable scepticism, but trials at other plants have confirmed the correctness of the solution.

The question arises, why should such an apparently small modification in mould design have such a profound effect on the ingot quality. An hypothesis which seems to meet the known facts is as follows:

As solidification proceeds in an octagon mould, the inner contour of the advancing walls of solidification gradually changes from octagonal to circular, owing to the quicker rate of freezing from the mould corners. The inner face of frozen metal is seeking to contract in the comparatively rigid framework formed by the earlier frozen metal and is, therefore, in tension. Under such a condition of tensile stress, internal tearing, or rupture, may occur at any weak place which may serve to act as a stress raiser; it will be remembered, above, that such internal tearing, when it occurred, was always at the hottest side of the ingot, i.e. where the frozen wall would be thinner than elsewhere. The tearing which occurs is interdentritic and, as the crack opens, some of the segregated liquor, layering the face of the advancing wall, flows back into it. It would appear that sharp-cornered or, in other words, deep-fluted octagons, by their effect in bringing about an earlier circular contour to the inner face of the wall of solidification, thereby ensure a more regular distribution of internal stress and so practically eliminate the risk of internal rupture.

Basal Cone Weakness

Internal cavities, in otherwise perfectly sound forgings (FIG. 9), led to an investigation as to their cause. Such cavities were only found if the forging had to be bored or trepanned and the disturbing feature was that they occurred in a position coinciding with the bottom third of the ingot, i.e. a position below the areas of 'V' segregation and secondary piping.

The form taken by the cavities suggested that opening up or rupture had occurred during forging of that area of the ingot where the advancing walls of horizontal and vertical solidification met.

In order to check on this hypothesis a 40 in. octagon ingot of Ni-Cr-Mo steel was sectioned (FIG. 1). It was found that interdentritic fissures did indeed occur at the top of the basal cone of the ingot (FIG. 10).

If the reduction done in forging is sufficient, such cavities are eliminated by welding. If, however, the reduction is only in the order of $2\frac{1}{2}$ to 1, they may be opened up.

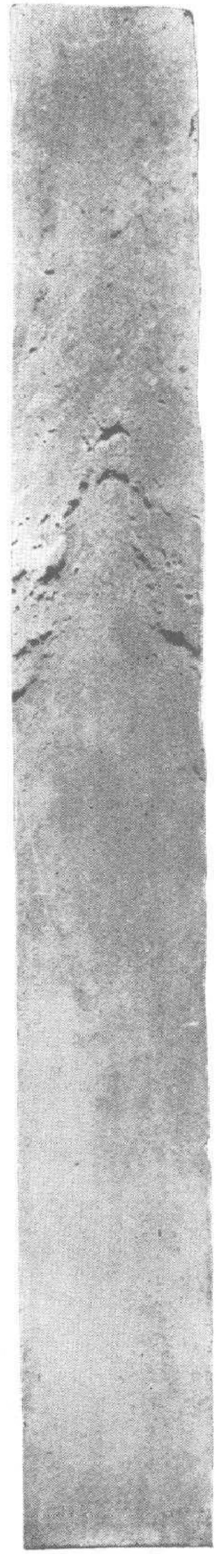

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FIG. 9 — CAVITIES IN TREPANNED CORE FROM LARGE FORGING

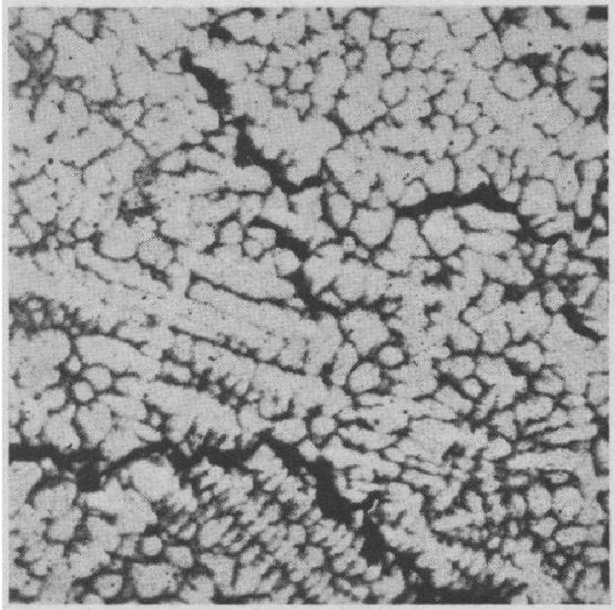

FIG. 10 — INTERDENTRITIC FISSURES IN 'AS-CAST' INGOT. TOP OF BASAL CONE

There are three ways by which the fault may be overcome, two of immediate practical application and one still in the experimental stage.

(1) A preliminary upending, by 50 per cent or so, of the ingot under the press serves to weld up any such internal weakness.

(2) The ingot may be made of such dimensions, length to breadth, that the top of the basal cone is adjacent to the 'hot top' or top discard portion. Such a procedure necessitates, for example, using a 60 in. octagon instead of a 40 in. octagon for a given ingot weight (FIG. 11). This entails much more forging work in the longitudinal direction and so impairs somewhat the transverse properties of the steel.

(3) An ingot of normal dimensions may be cast, but so arranged that preferential freezing occurs from the bottom up. Since the rate of vertical solidification cannot be materially increased, either by using copper bottom plates or by mould walls thickened at the bottom end, the only thing that can be done is to materially retard the rate of horizontal freezing.

This has been achieved in the following way:

A 25 in. octagon ingot was cast small end up, and without a 'hot top', and stripped 10 min. after casting. A small end up mould without a 'hot top' was necessary in order to permit of such rapid stripping.

The stripped ingot, standing on a very heavy cast-iron bottom plate, was then covered with a large mould lined with insulating bricks (FIG. 12).

On sectioning, the ingot was found to be very good for one cast small end up, without a feeder head (FIG. 13). Secondary piping was entirely absent and there was only a trace of 'V' segregation. The weakness associated with the top of the basal cone was also absent. The difference in pattern of the 'A' segregate from that of a normally cast ingot was also very noticeable.

Still better results might perhaps have been achieved, had the hood used carried radiator heating elements in addition to the insulating lining.

So far as it has been possible to calculate, the ingot appears to have taken about 30 hr. to solidify, the rate of horizontal solidification having been approximately $\sqrt[0.9]{T} = d$, where T equals time in minutes

FIG. 11 — 63 IN. OCTAGON INGOT, 22 TONS TOTAL WEIGHT, 15 TONS CHILL WEIGHT

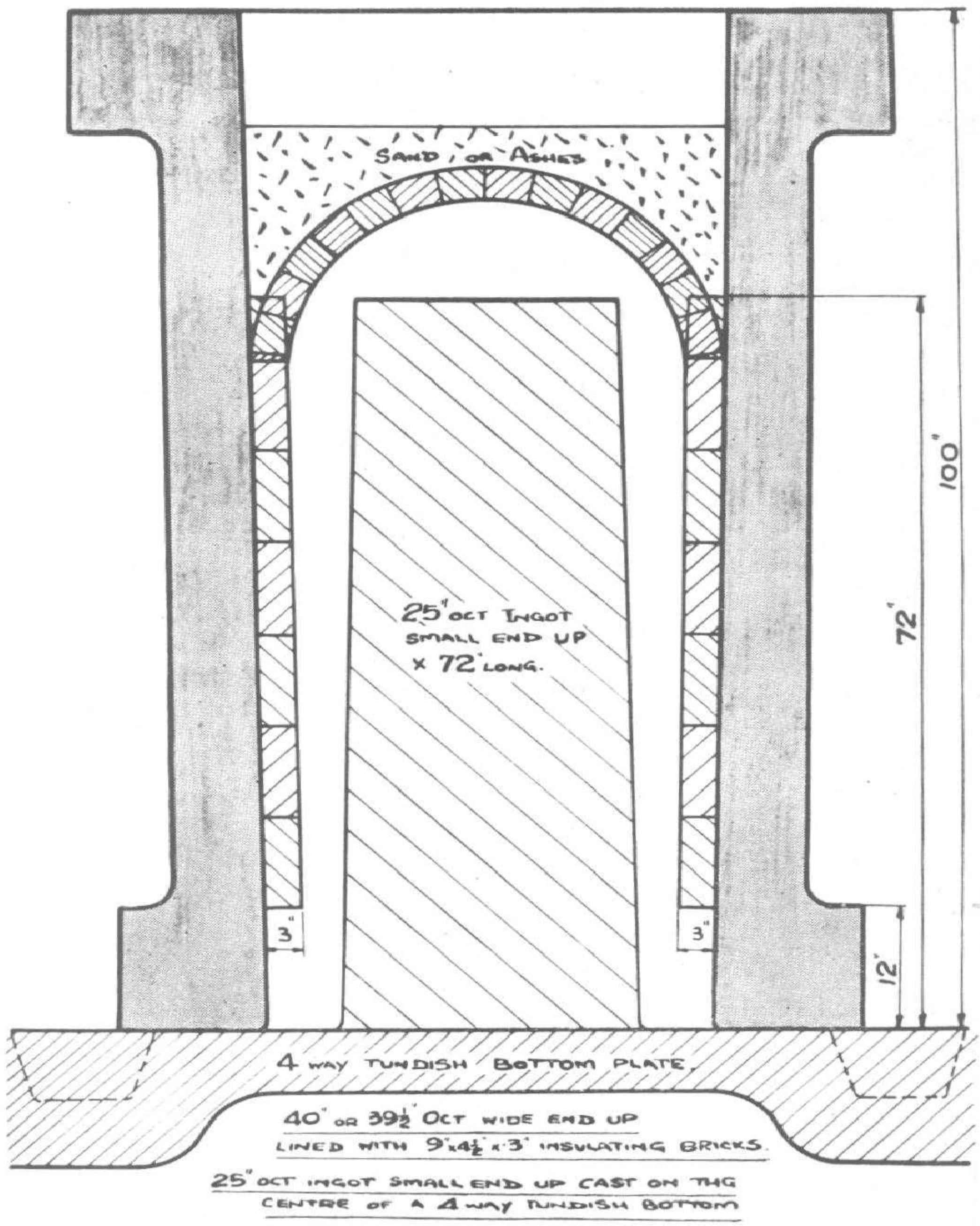
SAND OR ASHES
25" OCT INGOT
SMALL END UP
X 72" LONG.
100"
72"
12"
3"
3"
4 WAY TUNDISH BOTTOM PLATE.
40" OR 39½" OCT WIDE END UP
LINED WITH 9"x4½"x3" INSULATING BRICKS.
25" OCT INGOT SMALL END UP CAST ON THE
CENTRE OF A 4 WAY TUNDISH BOTTOM

FIG. 12

and *d* equals thickness in inches of frozen metal.

In spite of this delayed solidification, i.e. 30 hr. or so instead of the normal $2\frac{1}{2}$ hr. for an ingot of this size, the degree of segregation was by no means abnormal as may be seen by reference to Table 2.

TABLE 2

	C	Si	S	P	Mn	
E just below pipe	0·33	0·276	0·045	0·036	0·78	All samples from axis of ingot
D just below V seg.	0·30	0·270	0·036	0·032	0·76	
C near centre axis	0·28	0·267	0·031	0·031	0·75	
B 13% from bottom	0·28	0·248	0·037	0·032	0·74	
G $8\frac{1}{2}$ in. from side	0·32	0·261	0·036	0·029	0·77	
F $8\frac{1}{2}$ in. from side	0·30	0·263	0·037	0·030	0·76	
A 4 in. from side in 'A' segregate line	0·33	0·252	0·044	0·029	0·78	

In conclusion the author thanks the directors of the Steel, Peech and Tozer branch of the United Steel Companies Ltd. for their permission to publish this paper and his colleagues for all the help they always so readily give him.

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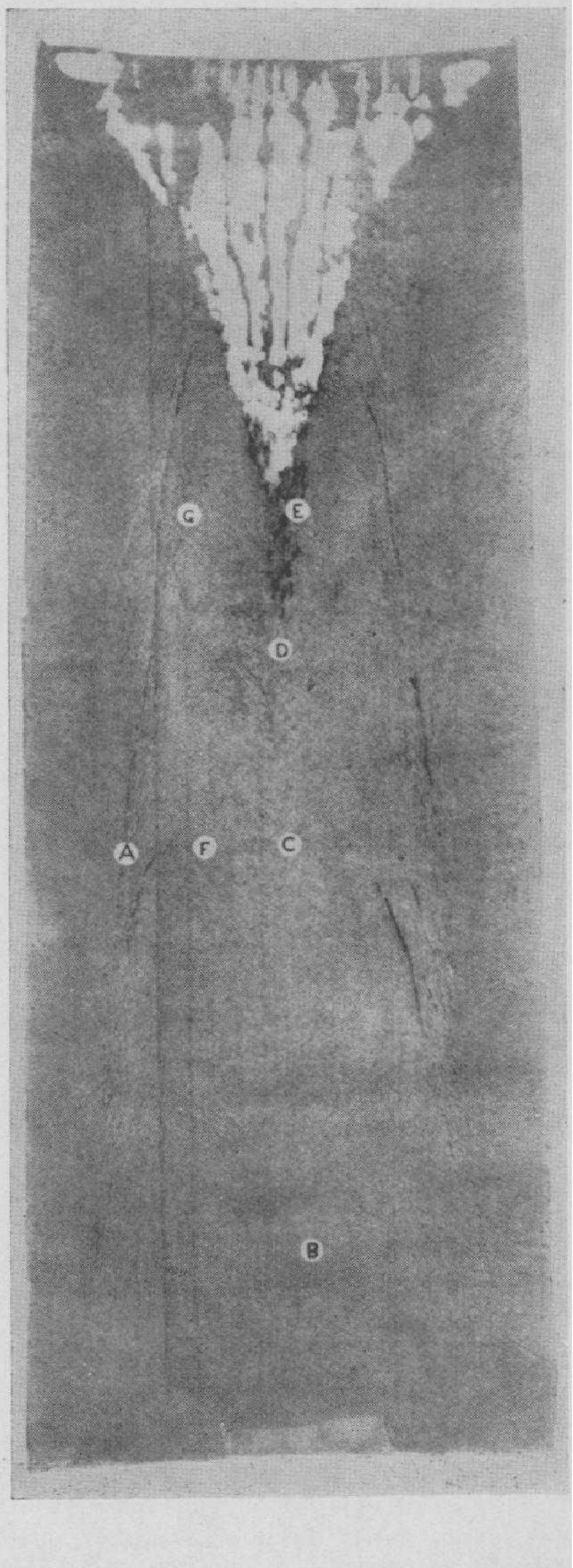

FIG. 13 — SULPHUR PRINT OF 25 IN. OCTAGON INGOT. RETARDED SOLIDIFICATION