INGOT TEEMING PRACTICE

In conventional ingot practice the mould may be thought of as a container that extracts heat from the molten steel, thus causing cooling and solidification. The temperature of the steel entering the mould, the method of teeming, the rate of filling, the shape of the mould, the solidification characteristics of the steel, and the effect of the atmosphere, all influence the surface and structure of the ingot. As bulk steelmaking is a batch, mass-production process, each furnace tap may produce a few large forging ingots, or many small rolling ingots. In either case, teeming temperature and teeming speed will, in practice, vary throughout the teeming of the cast. Hence ingot quality control necessitates knowledge of the optimum teeming conditions required, and the precise effects on ingot quality of variations from these conditions. Ingot structural or internal quality depends mainly upon relatively stable factors for each individual heat, such as the type of steel, the shape and design of the ingot and ingot mould. Ingot surface and subsurface quality is more sensitive to minor changes in teeming practice.

Causes of Ingot Surface Defects Dependent on Teeming Practice

(1) Cracks
(a) Restrictive cracks—hanger cracks and fin cracks.
(b) Cracks associated with mould surface irregularities. As the solidified ingot skin cools, it contracts. At this initial stage in the freezing of the ingot the skin is thin and its strength low. Hence any physical aspect of the mould-ingot entity that restricts free contraction is likely to give rise to stresses exceeding the strength of the solidified skin, which then cracks or tears normally to the stress. Badly fitting superimposed feeder heads will give hanger cracks, which generally occur immediately below the head-mould junction. Flash, caused by metal penetrating between the mould and its baseplate, can give rise to basal cracks. Fins, associated with the use of badly cracked moulds, can cause longitudinal cracks on the ingot. Similarly, mould irregularities, such as deep crazing or gouges, can cause restriction cracks in the ingot surface. Preventing this type of defect calls for strict supervision of pit preparation, and a routine mould and bottom-plate preparation procedure which eliminates, as far as practicable, the use of damaged, dirty, or badly fitting moulds, plates, or feeder heads, and obviates the necessity of setting moulds that are too hot or inadequately cleaned. To achieve this, it is necessary to lay down standard pit preparation procedures for each type of ingot and quality of steel made.

(c) Transverse cracks—facial—corner. The causes of these types of crack are more complex, but the main factors involved are teeming conditions—principally teeming rate and temperature. Cracks arise during the initial process of solidification, when the strength of the thin, semi-plastic, ingot skin is insufficient to withstand the ferrostatic pressure exerted by the liquid steel. Hence factors which tend to increase the incidence of cracking are (i) too high teeming temperature; (ii) too rapid teeming rate; (iii) hot moulds; and (iv) unequal cooling rates, e.g., due to slag patches on the ingot or mould surface, or to off-centre teeming into the mould. Transverse cracks on the ingot become distorted in rolling, and form "pulls" on the rolled product.

(d) Longitudinal cracks—facial—corner. Longitudinal corner cracks are often caused by incorrect mould design, in conjunction with fast teeming and/or excessive teeming temperatures. Within a few minutes of casting, the initial chill skin...
shrink slightly and leave a gap between the ingot and the mould wall. Dendrites are meanwhile forming and advancing into the ingot normally to the surface, interspersed with relatively impure material still in liquid form. As casting proceeds the ferrostatic pressure becomes greater near the bottom of the ingot. In cases where teeming speed is excessive, the ferrostatic pressure builds up rapidly, and can push the chill skin towards the mould wall. This generally occurs away from the ingot corner. The result is a cleavage in the dendrites which immediately fills with liquid segregate. This cleavage occurs at the weakest point, i.e., where the planes of dendrites meet at an angle at the corner of the ingot. In fact, as the corners chill more rapidly than the faces of the ingot, the weakest point is generally just offset from the corner. The result is corner segregation, and in the more extreme cases longitudinal corner cracking.

![Formation of surface ripples.](image1.png)

Slower teeming and cooler metal enable the skin strength to build up sufficiently to withstand the ferrostatic pressure. Sharper ingot corners increase the chilling at the corner relative to the face and this strengthens the ingot corners. Lower carbon steels are more prone to this defect and nickel steels are the most troublesome. Longitudinal facial cracks may form during the initial stages of solidification, as a result of horizontal stresses in the ingot skin arising from ferrostatic pressure build up or from restrictions to the free expansion or contraction of the ingot skin. These cracks should be differentiated from panel cracks, which are longitudinal face cracks occurring much later in the process. Longitudinal facial cracks on ingots give rise to "splits" on the rolled product.

- **Basal cracks.** Basal cracks, as the name suggests, occur in the bottom of the ingot and are usually caused by fins or flash preventing free contraction of the ingot skin.

- **Panel cracks.** Panel cracks arise from stresses in solid ingots which are cooled too rapidly, and so are not usually apparent when the ingots are first stripped from the moulds. They generally start internally and subsequently open up to the ingot surface as deep longitudinal facial splits. Medium and high-carbon steel, particularly if fine grained with aluminium, are susceptible to panel cracking. An alloying addition of titanium will usually obviate the trouble.

- **Rippled Surface** Examination of ingots as they are stripped, or after they are cold, will often reveal narrow bands of horizontal ripples, similar to waves on the surface of a liquid. These can extend over the full height of the ingot, or may be evident only in the upper half or third. Ripples cannot truly be considered as a defect, as they give rise to no yield loss or reduction of quality at later stages. In fact, fine ripples are usually an indication of good teeming practice. Formation of ripples is illustrated in Fig. 1. They are caused by incipient freezing of the meniscus of steel as it rises in the mould. A slight increase in teeming speed will eliminate ripple formation and result in a steady "rolling" rise of steel against the mould wall, giving a smooth ingot skin. Decreasing teeming speed, or lower temperature, results in wider and more undulating ripples, due to the increased depth of the meniscus frozen during teeming.

(3) **Double Skin** Generally found at the bottom end of ingots, double skin is due to the metal striking the bottom plate and splashing onto the mould walls. A steel "box" is formed which shrinks from the mould wall and is later engulfed by the rising metal. Steel subsequently flows between the mould wall and the initially formed box, giving a curtain effect on the ingot surface. This curtaining is often associated with horizontal cracking. Double skin formation is shown in Fig. 2. Metal splashed onto the mould wall, and double skin, give rise to "shell" or "spilliness" on the rolled product.

(4) **Teeming Lap** With a slow rate of rise in the mould, and a low teeming temperature, the meniscus will freeze to a considerable extent, and ripple formation is converted into lap formation. The rise of metal up the mould wall momentarily ceases until increasing pressure creates a secondary meniscus which then envelopes the original meniscus at the mould wall. This is illustrated in Fig. 3. Teeming laps can be prevented by suitable control of teeming speed and temperature, or by the use of mould dressings or additives.

(5) **Double Teem or Cold Shut** This is a severe form of teeming lap which occurs when the rise of metal in the mould ceases completely, for a shorter or longer time, because of stopper trouble, accidental shut-off, runner break-outs, etc.

![Formation of double skin.](image2.png)

(6) **Slag Patches, Surface and Subsurface Non-metallic Inclusions—Sand and Dirt** Small non-metallic particles embedded in the ingot arise from runner bricks, ladle refractories, etc., or from deoxidation products. Teeming into inadequately cleaned moulds can have the same effect.

(7) **Spongy Top** Spongy top is an irregular eruption of steel on the top of effervescing and partly killed steels, caused by gas evolution during solidification of the upper surface.
(8) Bootleg
A sunken top of a rimming ingot is caused by excessive gas evolution when the rimming action has not been adequately controlled by deoxidants.

(9) Flash and Fins
This is a thin plate or slice of metal on the ingot, resulting from steel flowing between the mould and the base plate, between the feeder head and the mould top or into mould cracks.

(10) Crazing
A "crazy-paving" pattern on the ingot surface corresponds to the craze pattern on the mould surface. This occurs with the use of old moulds which have become heat crazed. The craze pattern may be either protruding or depressed.

(11) Scab
Scab is a bulge, or protrusion, on the ingot surface, corresponding to a depression or gouge in the mould wall. If very severe it can cause difficulty in stripping.

(12) Skin Holes, Pitting or Surface Blowholes
Blowholes in the ingot surface are often associated with dampness on the mould walls, or the entrapment of moisture or volatile-mOULD dressings in the crazed network of old moulds.

Temperature and Teeming Speed
Numerous studies of the occurrence of surface defects on ingots have clearly shown the influence of teeming temperature and teeming speed on product quality and yield. Longitudinal cracks and teeming laps are particularly important, in that their presence defines the upper and lower limits of temperature and speed. Major cracks in ingots may be either transverse or longitudinal. It is generally accepted that longitudinal cracks, particularly facial cracks, are associated with high teeming temperature or excessive teeming speeds. Transverse cracks, on the other hand, may be associated with these factors, but are often also associated with restriction effects, such as slag patches, double skin, badly fitting feeder heads, etc.

It should be noted that slag patches are particularly deleterious in round moulds. The presence of slag on the mould wall reduces the solidification rate, creating a localised thin initial ingot skin. Circumferential stress is concentrated at this position and cracking is more likely. Effects of variation of teeming speed and temperature on the occurrence and severity of longitudinal cracks and teeming laps have been shown graphically by Thomas5 (Fig.4). It will be seen that there is an optimum temperature which will result in minimum defects and maximum yield. Reduction in temperature increases the liability of teeming-lap formation, whereas increase in temperature increases the incidence of cracking. Similarly, teeming slower than the optimum rate will increase the tendency to lapping, and teeming faster than standard will increase the cracking tendency. The units along the abscissa and ordinate of Fig 4 vary with the type of steel, and the ingot size, and there are ranges of values which will give minimum ingot surface defects. In practice, however, these ranges are often very short, and it is not always possible to eliminate defects entirely throughout a cast of steel.

Steel rising up the inner wall of an ingot mould during teeming may be represented diagrammatically as in Fig.1. Surface tension controls the angle of contact of molten steel and solid mould wall at point (a). The surface tension of steel is roughly 1500 dynes/sq cm, and the height, of the meniscus can be shown to be of the order 0.2 to 0.25 in (0.5 to 0.635 cm). With a plain, uncoated cast-iron mould, the contact angle is 120 to 140°. When the teeming conditions are correct the steel will appear to "roll" up the mould wall, and point (a) will travel up the mould wall at a uniform rate.

If one imagines the action to be frozen at an instant of time, then from point (b) downwards a solid skin of steel will be formed, thickening with increasing distance below (a). The rate of formation of the ingot skin is dependent upon teeming temperature (ie, the superheat of the steel) and the rate of heat abstraction by the mould wall. The thickness of skin is relatively thin at the start of solidification.

\[ D = k\sqrt{t} - c \]  

where 

- \( D \) is the thickness solidified;
- \( t \) is the time from start of solidification;
- \( k \) is a constant;
- \( c \) is a constant dependent upon steel superheat.

At some considerable distance below (a), representing approximately 3 in of teeming time, contraction of the ingot skin, due to cooling, will result in an air gap forming between the ingot skin and the mould wall. This is often attributed to a simultaneous contraction of the ingot and expansion of the mould, but although high compressive stresses undoubtedly build up in the innermost layers of the mould wall, which will have attained a temperature of 600 to 700°C at this time, it is doubtful if this will result in very much expansion of the mould as a whole, since the outer surface of the mould will have barely increased in temperature at all. Mackenzie and Donald9, however, consider that for a 11 in (280 mm) radius round mould the
resultant air gap at stripping was of the order of 0.2 in (4 mm). They show that, assuming Young's Modulus to be independent of temperature and stress, the mould radius could increase by 0.024 in (0.6 mm) in the first 3 min after teeming, and by 0.031 in (1.4 mm) after 30 min. This would mean that the initial air gap is due mainly to contraction of the ingot skin but partly also to expansion of the mould.

Work by Buttler and Glaisher on the determination of surface stresses in ingot moulds, and later studies by Goureau and Duflot, showed that high tensile stresses occur practically from the start of teeming, reaching a maximum of 50 or 60% of the ultimate tensile strength of the mould iron after 3 min. This tends to confirm that expansion of the ingot mould contributes to the formation of the air gap which occurs usually about 4 min after the start of teeming. Taking Young's Modulus as $15 \times 10^6$ lb/sq in and ultimate tensile strength as 25,000 lb/sq in for cast iron; then an outer surface stress of 50 to 60% of ultimate tensile strength after 3 min corresponds to a strain of 0.021 in (0.55 mm), i.e., an air gap of 0.011 in (0.275 mm) for a 25 in mould. The actual gap due to mould expansion will, in fact, be slightly greater than this by virtue of the thermal expansion of the outer face of the mould. These figures agree well with Mackenzie and Donald's work.

On the other hand, Efimov maintains that expansion of the internal surface of the mould is practically absent during the first 3 min to 5 min of solidification of the steel. He says that direct measurement of the deformation of the mould walls has shown that expansion of the inner surface of the mould occurs only after the fifth to tenth minute after teeming, when the outer surface of the mould reaches about 200°C. Measurements on a mould of 7.2 in (180 mm) wall-thickness and inner-face temperature 650°C, indicate a displacement of 0.01 to 0.014 in (0.25 to 0.35 mm).

Hence, he maintains that air-gap formation depends only upon contraction of the ingot.

The formation of the air gap at point (c) in Fig 5 means that the thin skin of relatively weak semi-plastic steel at this point has to withstand ferrostatic pressure of steel equivalent to depth (a) (c). If the teeming temperature is high, the skin at point (c) will be very thin, and since, at this time, the skin is generally not completely uniform in thickness, slight undulations or variations in thickness will result in excess stresses at the thinnest parts, and cracks may well result. Similarly, if the teeming rate is too high, ferrostatic pressure will build up more rapidly and the stress will be too great for the ingot skin to withstand.

Decarburisation observed around ingot-surface breaks of this type in plate-steel and rail-steel killed ingots, indicates that the cracks were formed at high temperature. They propagate interdendritically, and liquid segregate has been shown to be present at the time of their formation.

This confirms hot-tearing in the initially formed skin as the mode of formation.

Reduction of the teeming temperature and/or teeming rate reduces an uneven rise of the steel meniscus. This is shown in Figs 1 and 3. If teemed in air, oxidation in combination with heat loss causes a solid oxidised skin to form over the meniscus, and the steel no longer rises steadily up the mould wall. As teeming continues, metal breaks through the meniscus some way in from the mould wall, and a secondary meniscus forms, which overlaps the frozen meniscus at (a), and a teeming lap results. Laps occur most particularly in steels containing such elements as Al, Mn, Si, or Cr, which tend to form an oxide film on the surface during teeming. Alloy steels with low to medium-chromium contents (0.5 to 2.0%) show reduced fluidity, and some increase in temperature may be necessary to counteract this.

At intermediate teeming rates and temperatures the rise of metal at point (a) changes from a uniform rolling motion to a rapid intermittent motion, with the formation of finely spaced ripples (Fig 1). This is caused by intermittent slight freezing of the meniscus at (a). Ripples in themselves are not considered to be deleterious, but are an indication that borderline teeming conditions are being attained, and any reduction in either freezing rate or teeming temperature is likely to give teeming laps.

The relationship between time from commencement of teeming and the ingot skin thickness, represented by the formula already given, is approximately true for the solidification of the whole ingot, but it is difficult to derive accurate expressions for the instantaneous freezing rate within, say, the first few seconds of teeming.

Heat abstraction prior to the formation of the air gap is entirely due to conduction normally into and through the mould wall. Mackenzie and Donald showed that the rate of heat transfer rises almost instantaneously, at the point of contact of liquid steel and mould wall, to a maximum of something over 2000 cal/sq cm/min. After the formation of the air gap this falls rapidly to a value of about 200 cal/sq cm/min.

Efimov postulates that the solidification rate of the ingot-surface layer is not defined by simple considerations of heat transfer to the mould alone, but also by the velocity of flow.