Having designed the ingot it then becomes necessary to design the container or mould into which the ingot is cast. The size and shape of the ingot are determined largely by ingot quality and production rate factors, and naturally the internal shape and dimensions of the mould conform to the external shape and dimensions of the ingot.

The principal objects of ingot mould design are to optimise the production rate of ingots and minimise the cost without detriment to ingot quality. These objectives can best be achieved by designing the mould for strength, rigidity, smoothness of internal faces, ease of handling and long life.

Almost all ingot moulds in current use for steel ingot manufacture are made of cast iron, hematite iron being preferred. Steel has been tried as an ingot mould material from time to time but almost invariably it suffers from distortion leading to difficulty in stripping the ingots. Since the early fifties spheroidal graphite iron moulds have been used, generally to date on an experimental basis, with limited success.

DESIGN FACTORS AFFECTING INGOT QUALITY AND YIELD

Although the ingot shape is largely determined by ingot quality considerations, there are certain aspects which affect mould life, and, hence, overall costs. In respect of these aspects some degree of compromise is necessary. This is particularly true of ingot taper, corner radius, mould contour and, for slab moulds, the broad side to narrow side ratio.

(1) Ingot Taper

In WEU ingots taper is necessary to produce a sound ingot free from secondary pipe and axial unsoundness. Generally the degree of taper required to achieve this will not exceed 0-5in/ft (42mm/m). Melting shop requirements do not impose a maximum limit to the degree of taper, but the rolling mill would prefer the minimum taper practicable in order to equalise working throughout the length of the ingot. With respect to mould life a certain minimum taper is required to ensure ease of stripping and hence minimise mechanical damage to the mould.

For NEU ingots quality considerations and rolling mill requirements coincide in that the taper should be as small as possible. The controlling factor is the amount necessary to ensure ease of stripping. This is generally agreed to be about ½in to 1in/ft (10 to 20mm/m), but is dependent to some extent on the size of the ingot. The criteria involved are the avoidance of “sticker” ingots which may involve mechanical damage to the mould in freeing them, and prevention of extended contact between the ingot and the mould face due to delay in formation of the air gap.

(2) Corner Radius

Corner radius is a minimum of 6% of the square root of the inside cross-sectional area of the mould. Excessive corner radius in square or rectangular moulds can lead to an increased incidence of ingot corner segregation and longitudinal cracking in susceptible steels. On the other hand, if the radius is too small, i.e., the corner is too sharp, then it can act as a stress raiser in the mould leading to mould corner cracking and premature failure. Similarly badly designed flutes in octagonal or multisided moulds can give rise to longitudinal cracking or rolling/forging laps in the ingots, or the development of incipient corner cracks in the mould.

The use of a graduated corner radius from one end of the mould to the other corresponding to the variation in cross-section due to mould taper provides an effective corner taper. This will help to promote ease of stripping. It may also be essential to avoid the aforementioned longitudinal cracking and lapping in multisided ingots.

(3) Mould Contour

For steels susceptible to ingot teeming cracks it is a recognised practice to use moulds with corrugated faces. The increased perimeter so obtained serves to promote faster initial cooling of the ingot skin, and, hence, enable it better to withstand the stresses due to ferrostatic pressure. Corrugations can, however, serve as stress raisers, and according to Fowler! provide a focal point for seam formation. Hence, if corrugations are used they must be carefully designed. Fowler suggests that a simple sine wave is best for control of both cracks and seams (Fig 1).
In the author's experience, however, a simple sine wave contour can lead to excessive vertical cracking in large forging ingots. For such ingots a fluted configuration appears to be best (Fig2) provided that the flute depth and ridge radius are designed to eliminate lapping during forging, while still capable of sufficiently relieving surface stresses during teeming.

Gruznov et al. advocate the use of asymmetrical (sawtooth) corrugations on large slab moulds, and claim that the use of such moulds reduces the time taken for the formation of the air gap between the ingot and the mould, thus providing a more rapid initial cooling and strengthening of the ingot skin. They claim that in order to prevent longitudinal crack formation in direct teemed slab ingots the initial ingot skin must be thicker at the rib projections on the ingot than at the depressions. This may be achieved by reducing the distance between corrugation apices, increasing the corrugation height, reducing the angle at which the faces converge and reducing the rib projection radius of curvature. High ribs cause ingots to stick as they cool and the serrations on the wide faces of slab ingots should therefore be asymmetrical and stepped. The mechanism of crack formation at rib projections is the same as that of corner cracks.

With corrugated moulds the contour of the mould inner surface intensifies the effect of the crazing by channeling the cracks into the corners, thus facilitating surface break-up. The effect is to reduce the mean mould life for corrugated moulds compared with equivalent plain moulds. Similarly, while the use of concave mould faces may be advantageous with regard to ingot quality by allowing some relaxation of ingot skin stresses, it could lead to swizzling or instability of the ingot on entry into the mill, especially on the narrow sides of slab ingots. The use of concave narrow side faces, however, could be advantageous in reducing "rolling overlap."

Fowler also states that experience has shown that relatively flat outer surfaces on the mould can serve to concentrate stresses with resultant splitting of the mould. On slab moulds such stresses will be concentrated on the narrow sides resulting in narrow side cracking. If the outer surfaces of the mould are curved and blended into the corners stress distribution tends to be more uniform. The optimum radius of curvature will depend upon the mould size and shape; slab moulds require different radii for the narrow and broad sides.

(4) Broad Side/Narrow Side Ratio (Mould Aspect Ratio)

Ideally the ingot shape should approach as closely as possible to the rolled product shape. This implies a high aspect ratio for slab moulds. High aspect ratios have a detrimental affect on mould life, however, due to the adverse stress distribution coupled with the increased risk of burning or scoring the broad faces through mis-alignment of the teeming stream with direct teeming. Also there may be an increased tendency for the mould to warp in service, and manufacture of moulds becomes more difficult if flat cores are required.

A high proportion of rimming steel ingots is made in slab moulds. Aspect ratios exceeding about 2:1 can adversely affect the rimming action.

(5) Manufacturing Tolerances

Relatively small variations in mould dimensions can produce sizable ingot weight variations; hence, it is important that the foundry should be able to manufacture moulds to reasonably tight dimensional specifications. Generally, medium-sized moulds are made to a tolerance of ±½ in (3·0mm) in cross-sectional dimensions and ±¼ in (6·0mm) on length. It is particularly important that the core be centrally placed otherwise mould walls of varying thickness may result leading to a high stress concentration at the thinnest section, and possibly to premature failure of the mould.

The inner faces of moulds should be smooth and free from blemishes. Failure to achieve this can result in early sticker troubles.

DESIGN FACTORS INFLUENCING MOULD LIFE AND CONSUMPTION

(1) Mode of Failure

Moulds are kept in service for as long as they can produce satisfactory ingots, or do not present a safety hazard. There are two principal modes of ingot mould failure, and several subsidiary ones. The repeated cyclic heating and cooling pattern to which moulds are subjected during their period of use produces considerable stresses within the mould wall, and growth and oxidation of the inner surface. The stresses sooner or later result in the mould wall splitting or cracking. Such cracks extend with each subsequent heat until the mould can no longer be used.

Growth and oxidation of the inner mould surface leads to the development of a crazed pattern, starting where the mould face gets hottest in service and spreading gradually over the entire inner surface. When, after an extended life, the crazing becomes very severe deeper cracks appear and the mould wall may split vertically often starting at the base and spreading throughout the length of the mould (Fig3). Generally, however, the mould becomes unserviceable before this stage is reached, either through increased difficulty in stripping the ingots from the moulds or through an increase in ingot surface defects.

Crazing may be "projecting" or "depressed" depending upon whether the predominant effect is either growth of the mould iron giving projecting crazing and fissures to a depth of ½ in (32mm) or localised oxidation of the surface resulting in a depressed, much shallower form of crazing perhaps to a depth of ⅛ in (6mm). The onset of
Crazing is mainly associated with the conditions of service and to a lesser extent with foundry variables. Mould cracks are usually vertical either on the face or in the corner, often starting from the open end of the mould, but not always (Fig 4). Horizontal cracks, though rarer do occur, particularly on rectangular moulds. Cracks may occur suddenly on the first heat, or may develop gradually after considerable service. The main factors affecting the incidence of mould cracks are foundry manufacturing procedures including sand mould rigidity and treatment of the mould after pouring, its treatment prior to use, the conditions of service and the mould design. Other less frequently occurring modes of failure include mechanical damage, often caused by rough treatment in stripping, but which can also be due to faulty design particularly with regard to the positioning and size of lugs, trunnions, and location tablets, etc; the burning of the inner surface of the moulds caused by off-centre teeming or teeming too hot. If the steel is teemed very hot it is possible for ingot and mould to become welded together. This happens most frequently at the base of the mould and can result in a piece of the mould being torn away in stripping. This is usually referred to as "torn seat".

(2) M/I Ratio

Mould life varies considerably according to the size, conditions of use, method of manufacture etc, and even for one mould type used in one melting shop a wide range of individual mould lives may be obtained. Mould consumption can be directly related to the cost of ingot production. It is vital therefore that the moulds be designed to attain minimum consumption and maximum life. These two terms are not necessarily synonymous and will therefore be defined.

Mould life is the number of ingots produced in a particular mould before it becomes necessary to scrap it. Figures quoted for mould life generally refer to the average life achieved by that particular type or design of mould used in one melting shop.

Mould consumption is the weight of mould "consumed" per ton of ingot cast, generally quoted in lb/ton. Too literal an interpretation of this might give the impression that the mould wears away with each heat teemed, and that ingots teemed later in the life of the mould are therefore bigger than those teemed when the mould is new. This is not so.

\[
\text{Mould Consumption} = \frac{\text{Mould Weight} \times 2240}{\text{Ingot Weight} \times \text{Mould Life}} \quad (1)
\]

or

\[
\frac{\text{Mould Consumption} \times \text{Mould Life}}{2240} = \frac{\text{Mould Weight}}{\text{Ingot Weight}} \quad (2)
\]

It is immediately obvious that for a given mould life mould consumption is minimised when the mould weight to ingot weight ratio (M/I) is a minimum.

(3) Wall Thickness

If we ignore the extra weight of lugs, trunnions location tablets, etc, then M/I ratio is a measure of the mean wall thickness of the mould. High values correspond to thick walls, low values to thin walled moulds. The former would be expected to give a high consumption because of the bulk of excess mould iron carried; the latter would be expected to give a high consumption because of increased susceptibility to cracking.

If M/I is plotted against mould consumption for any particular mould type one would logically expect an inflexion in the curve to indicate minimum mould consumption at the optimum M/I value (Fig 5). Moulds with excessively thick walls failing by crazing will give a high mould consumption as will moulds with excessively thin walls failing by cracking. The relationship between M/I ratio and mould consumption was first investigated by N H Bacon, who made recommendations for the optimum M/I ratio according to mould type, size, etc (Fig 6).

Experience has shown that the major factor influencing mould life is concerned with the conditions of use in the steelworks. Consequently, the same mould can give considerable differences in average life and consumption when used in different melting shops. Data are inevitably

3 Examples of 4ton square ingot moulds after use: (a) inside surface of corrugated mould wall showing crazing after 158 heats; (b) inside surface of plain mould wall showing crazing after 222 heats; (c) inside surface of plain mould wall showing crazing and cracking after 146 heats; (d) inside surface of plain mould wall showing cracking and slight crazing after 107 heats.

4 Cracked 4ton square ingot mould.
ature of the process. It does not 
yulds otherwise identical, but of 
yaring wall thickness, are used in 
type of ingot under identical service 
quite naturally there has been a 
part of steelmakers to use moulds 
atio, say, less than 0.8 for fear of 
re. Hence information is lacking 
the following equations for calculating the mean wall 
ickness in inches from the M/I ratio.

Wall Thickness = 0.21 M/I \times A \text{ in}

for round, octagonal or nearly 
square moulds - where A is the 
cross-sectional area in sq in.

Wall Thickness = 0.20 M/I \times A \text{ in}

for slab moulds with an aspect 
atio of 2:1.

But, as pointed out in the BISRA Ingot Moulds 
Sub-Committee Third Report\(^5\) the wall thickness thus obtained 
will not be the best in all circumstances. Amendments 
may be necessary to suit the particular conditions of use 
especially with respect to the type of casting pit used and 
the spacing of the moulds in the pit.

The likelihood of mould cracking is inversely proportional 
to the mean wall thickness. So if the walls are thick enough 
 major cracking can be eliminated, but at the cost of an 
excessive mould consumption. If the wall thickness is 
uced in order to minimise mould consumption then 
the conditions of manufacture of the mould, the strength 
of the mould metal, the conditions of use in the steelworks, 
and the design of the mould must also be optimised.

Variation in mould wall thickness depends upon the ingot 
shape. The simplest mould is round for which wall 
ickness is uniform throughout the cross-section, but may 
vary from top to bottom (Fig8). Octagonal and multisided 
moulds are slightly more complex in that flutes and 
corners are introduced. For these moulds the outer 
 contour may follow the inner contour (Fig9) with or 
without curvature of the outer faces; or may in fact be 
circular (Fig10). In the latter case face thickness is slightly 
greater than corner thickness and the M/I ratio is increased 
accordingly. It is generally necessary to thicken the mould 
at each open end, especially with larger moulds in order to 
strengthen the mould and counteract the initiation of 
 cracks. There is a body of opinion, however, which 
considers such strengthening bands unnecessary, or even 
detrimental.

Square moulds may have flat or bowed faces (Figs11 a-

12). In practice this seems to have little effect on mould 
provision provided that the wall thickness is adequate. The 
corner thickness should, however, always be slightly less 
han the centre wall thickness. The BISRA Ingot Moulds 
Sub-Committee\(^5\) recommends a corner thickness of 95\% 
of the centre face thickness, and quote an example of a 
to the provision of lugs, 
even strengthening bands\(^6\) 
within the mould and act 
ing mould life. Several 
isotherma pattern for 
thers have assessed the 
vestigations showed that 
outer faces of square or 
ed within a few minutes 
ing. This corresponds to 
ential through the mould 
modified Tomlinson strain 
in three directions at 60°.
lacking owing to the nature of the process. It does not often happen that moulds otherwise identical, but of varying M/I ratios or varying wall thickness, are used in the production of one type of ingot under identical service conditions. Also, and quite naturally there has been a marked reluctance on the part of steelmakers to use moulds with a very low M/I ratio, say, less than 0.8 for fear of premature mould failure. Hence information is lacking the following equations for calculating the mean wall thickness in inches from the M/I ratio.

Wall Thickness = 0.21 M/I \times A \text{ in}

for round, octagonal or nearly square moulds, where A is the cross-sectional area in sq in.

Wall Thickness = 0.20 M/I \times A \text{ in}

for slab moulds with an aspect ratio of 2:1.

But, as pointed out in the BISRA Ingot Moulds Sub-Committee Third Report\(^5\) the wall thickness thus obtained will not be the best in all circumstances. Amendments may be necessary to suit the particular conditions of use especially with respect to the type of casting pit used and the spacing of the moulds in the pit.

The likelihood of mould cracking is inversely proportional to the mean wall thickness. So if the walls are thick enough

major cracking can be eliminated, but at the cost of an excessive mould consumption. If the wall thickness is reduced in order to minimise mould consumption then the conditions of manufacture of the mould, the strength of the mould metal, the conditions of use in the steelworks, and the design of the mould must also be optimised.

Variation in mould wall thickness depends upon the ingot shape. The simplest mould is round for which wall thickness is uniform throughout the cross-section, but may vary from top to bottom (Fig8). Octagonal and multisided moulds are slightly more complex in that flutes and corners are introduced. For these moulds the outer contour may follow the inner contour (Fig9) with or without curvature of the outer faces; or may in fact be circular (Fig10). In the latter case face thickness is slightly greater than corner thickness and the M/I ratio is increased accordingly. It is generally necessary to thicken the mould at each open end, especially with larger moulds in order to strengthen the mould and counteract the initiation of cracks. There is a body of opinion, however, which considers such strengthening bands unnecessary, or even detrimental.

Square moulds may have flat or bowed faces (Figs11 to 12). In practice this seems to have little effect on mould life provided that the wall thickness is adequate. The corner thickness should, however, always be slightly less than the centre wall thickness. The BISRA Ingot Moulds Sub-Committee\(^5\) recommends a corner thickness of 95% of the centre face thickness, and quote an example of a
mould type inadvertently made with corner thickness greater than the face thickness, viz:

<table>
<thead>
<tr>
<th></th>
<th>Abnormal Mould</th>
<th>Normal Mould</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness at centre of face</td>
<td>4(\frac{in}{114\text{mm}})</td>
<td>4(\frac{in}{108\text{mm}})</td>
</tr>
<tr>
<td>Thickness at corners</td>
<td>4(\frac{in}{120\text{mm}})</td>
<td>4(\frac{in}{101\text{mm}})</td>
</tr>
<tr>
<td>Mould weight</td>
<td>85(\text{cwt (4320kg)})</td>
<td>73(\text{cwt (3800kg)})</td>
</tr>
<tr>
<td>Mean life</td>
<td>110</td>
<td>134</td>
</tr>
<tr>
<td>Consumption</td>
<td>23(\text{lb/t}})</td>
<td>16(\text{lb/t}})</td>
</tr>
</tbody>
</table>

Similarly with rectangular slab moulds the corner thickness should be less than the centre face thickness; also it is recommended that the broad side of the mould be made thicker than the narrow side. The incidence of cracking in ingot moulds can be related to the distribution of stresses in the mould wall in service; which can be related to the isotherm pattern developed during and after teeming the ingot. Abrupt changes in section or wall thickness due to the provision of lugs, trunnions, or location tablets, or even strengthening bands can affect the isotherm pattern within the mould and act as stress raisers, thus reducing mould life. Several investigators have determined isothermal patterns for various types of mould. Others have assessed the stresses in the mould wall by strain measurement on the mould outer faces. These investigations showed that the maximum stress on the outer faces of square or rectangular moulds was attained within a few minutes after the commencement of teeming. This corresponds to the maximum temperature differential through the mould wall. Butler and Glaisher used a modified Tomlinson strain gauge for measuring the strain in three directions at 60° to each other on the outer surface of moulds during use in a steelworks. By assuming certain stress/strain relationships according to the temperature of the mould iron, and allowing for thermal expansion they calculated that stresses of approximately 70% of the ultimate tensile stress were developed during the first few minutes after the commencement of teeming. The stresses were initially mainly vertical, but became horizontal after 7 or 8 min. Goureau and Duflot used electrical resistance strain gauges on 3.6-ton square moulds. They recorded high tensile stresses from the start of pouring with a maximum elongation at about 70°C outside mould wall temperature. They found the initial stress to be horizontal becoming vertical after 15 min. There is an element of doubt about the stress figures obtained because the tensile strength of the iron for any particular mould cannot be measured accurately without destroying the mould, but it is evident that considerable tensile stresses develop in the outer layers of the mould wall. For round moulds the isotherm pattern is much simpler;
the isotherms being uniform and equally spaced so that, in theory at least, all points on the outer surface of round moulds reach the same temperature at any particular time. Stress over the outer surface is equalised and, if the mould wall thickness is adequate, small round moulds are virtually indestructible.

11 Square mould—flat faces.

12 Square mould—bowed faces.

13 Square mould—modified in order to obtain a more uniform isotherm pattern (British Patent 1,086,946).

made of spheroidal graphite iron. It was thought that the greater ductility and higher tensile strength of SG iron would increase the mould's resistance to thermal shock and would counteract the tendency to corner cracking. While the improved ductility has led to failures due to excessive distortion, promising results have been obtained.

References
4 N H Bacon: JISI, Jan 1948, pp81 to 95.
6 A P Banks: private communication.
11 British Patent No 1,086,946.