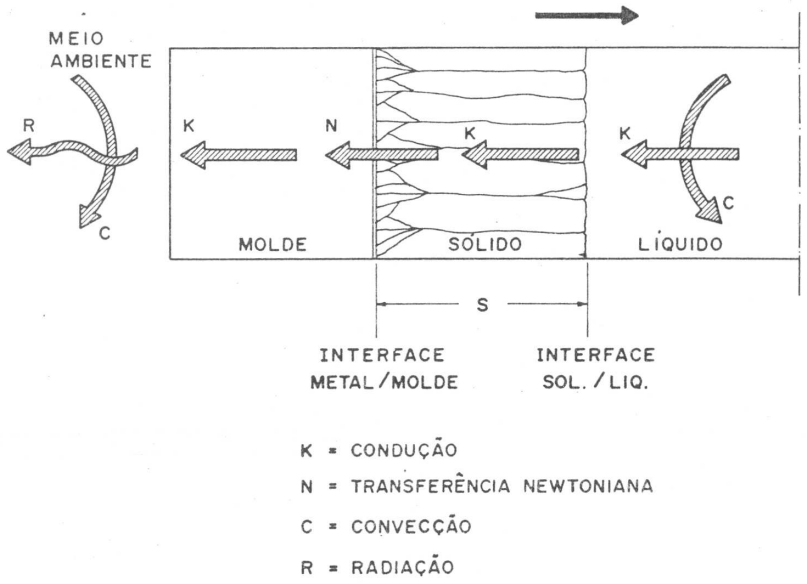
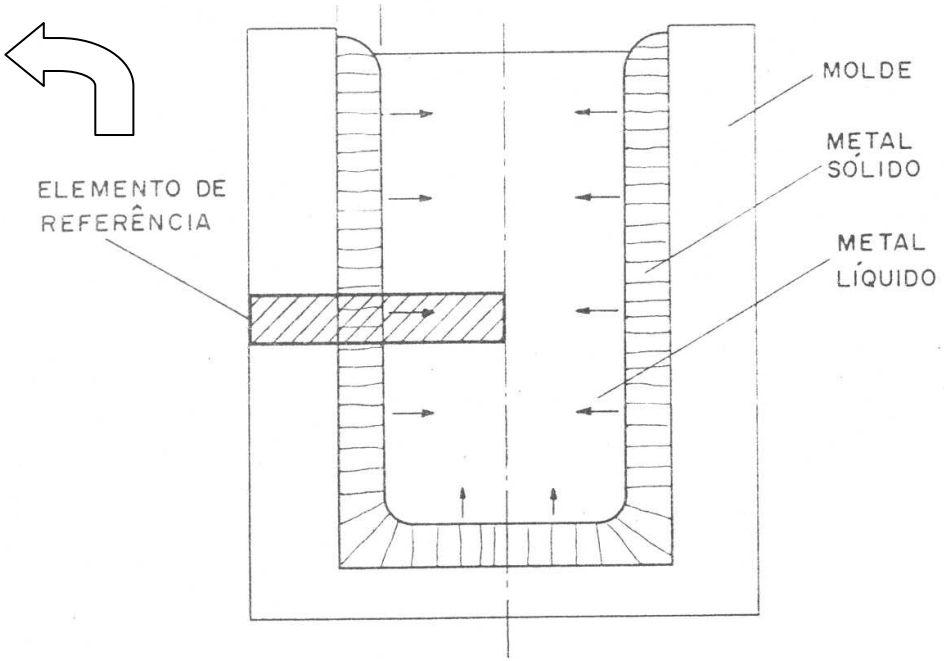
# Fundição

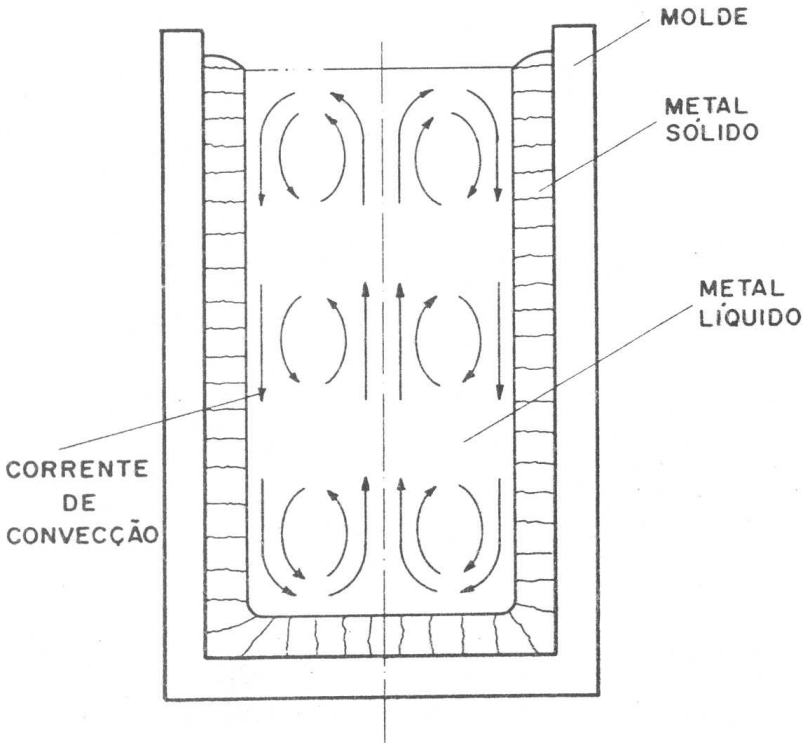
- Projetos de Moldes

# Fluxo de calor e direção de crescimento



# Formação da macroestrutura




Filme

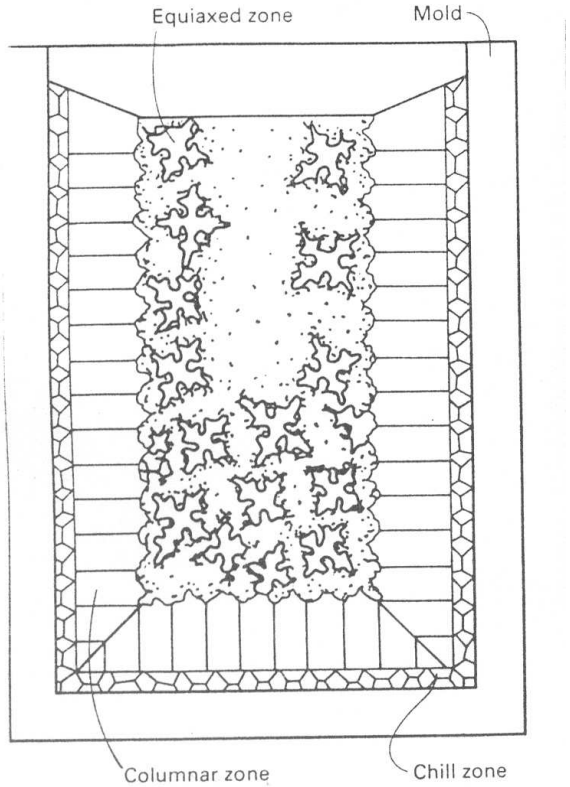
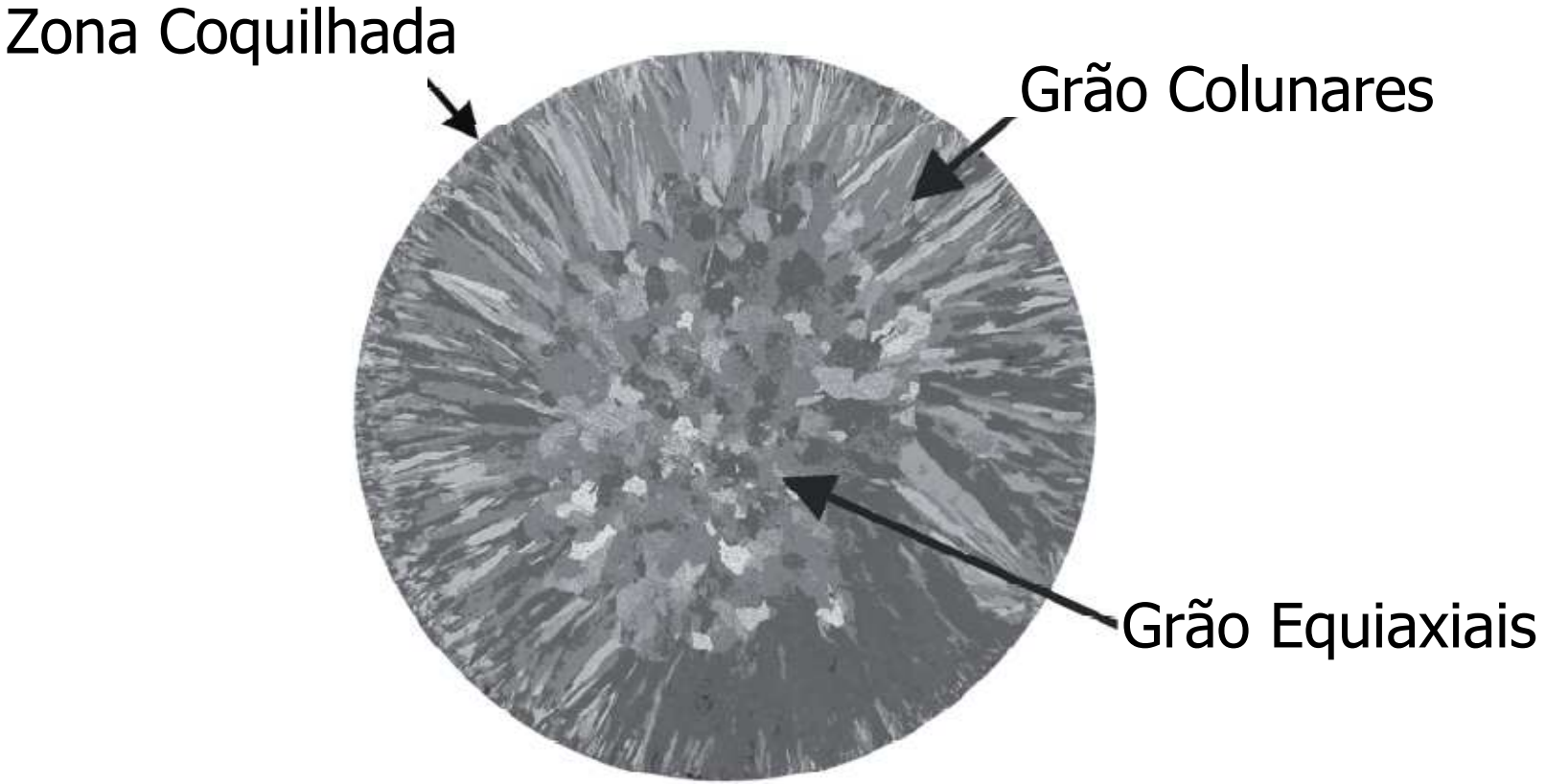
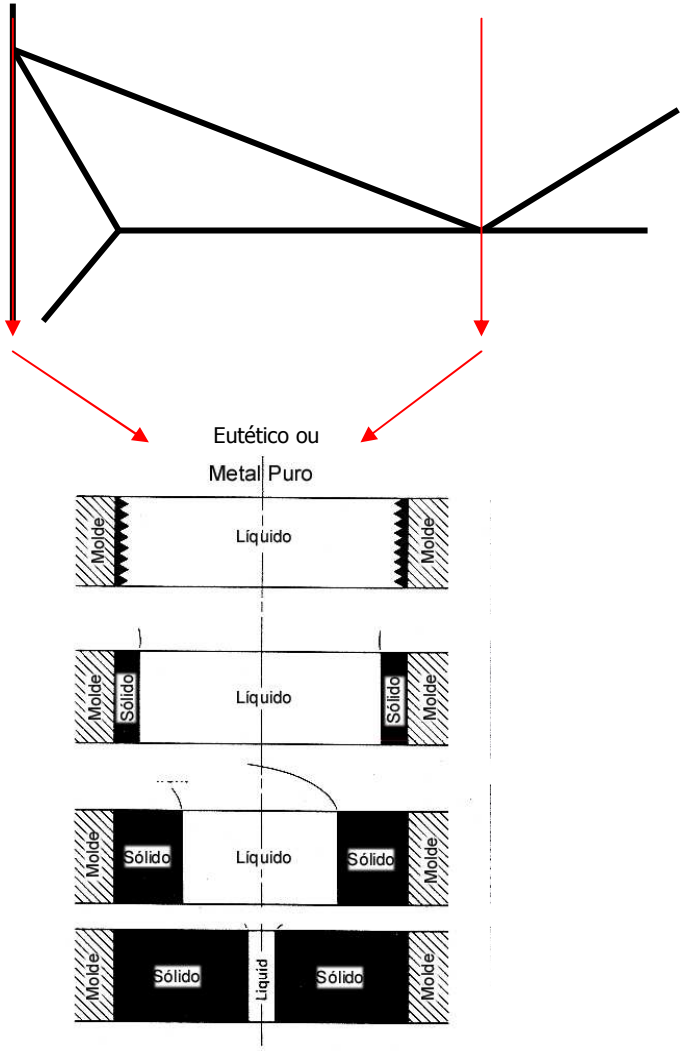



**Fig. 11** Schematic of microstructure zone formation in castings. Directional solidification conditions give rise to a columnar zone, while an equiaxed zone is formed at the center where the liquid is undercooled.

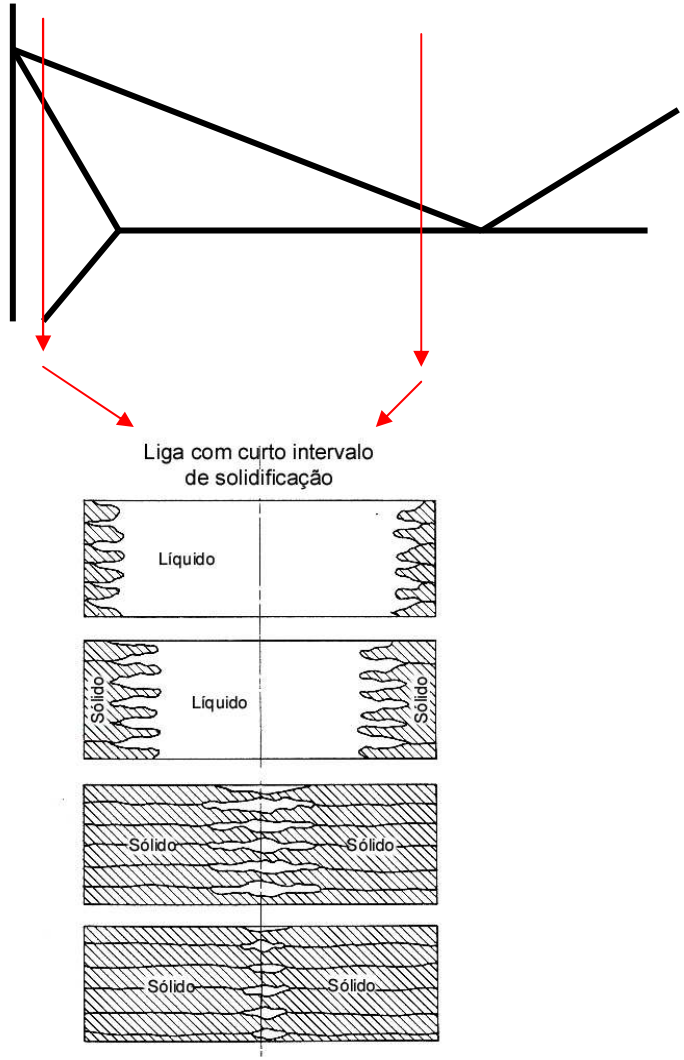
# Macroestrutura



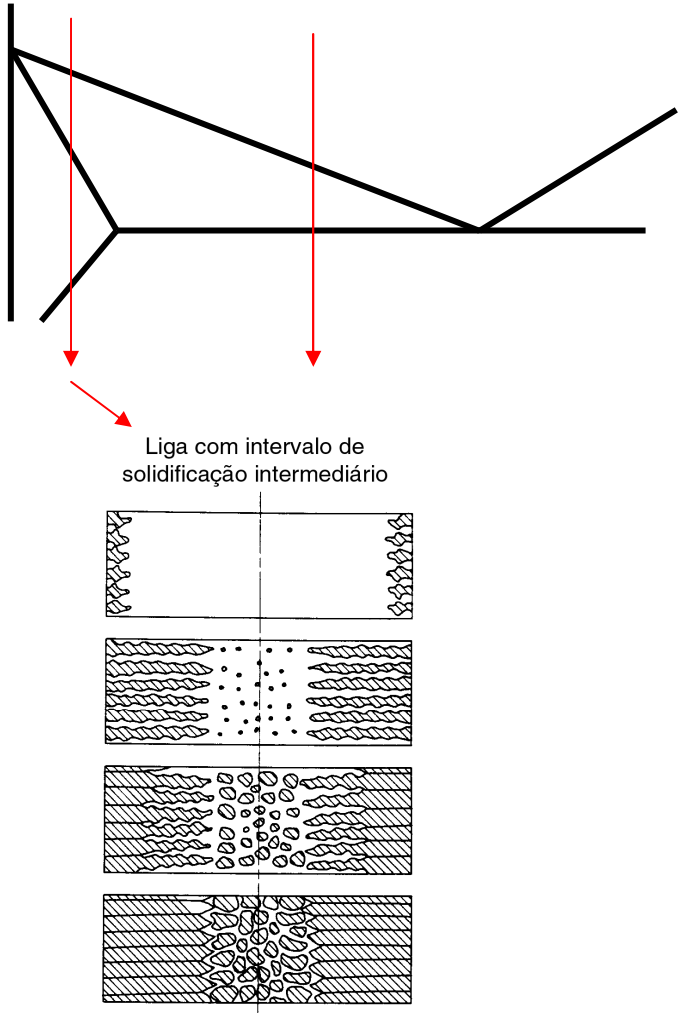
# Intervalo de Solidificação e a macroestrutura



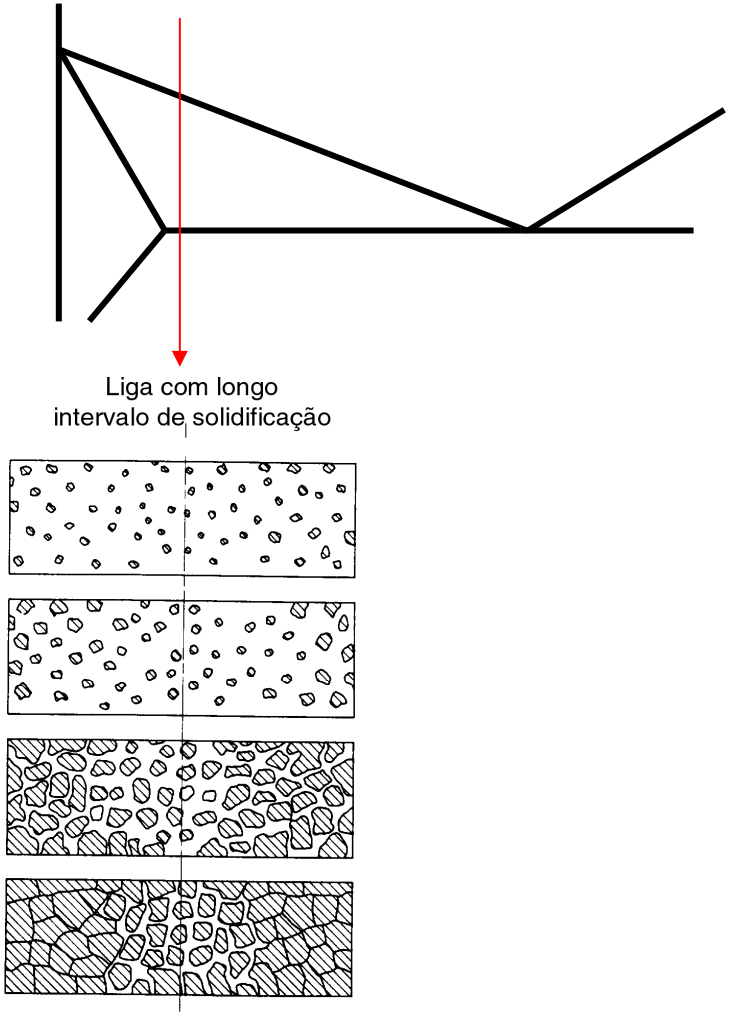
# Intervalo de Solidificação e a macroestrutura



# Intervalo de Solidificação e a macroestrutura



# Intervalo de Solidificação e a macroestrutura



# Contração na Solidificação

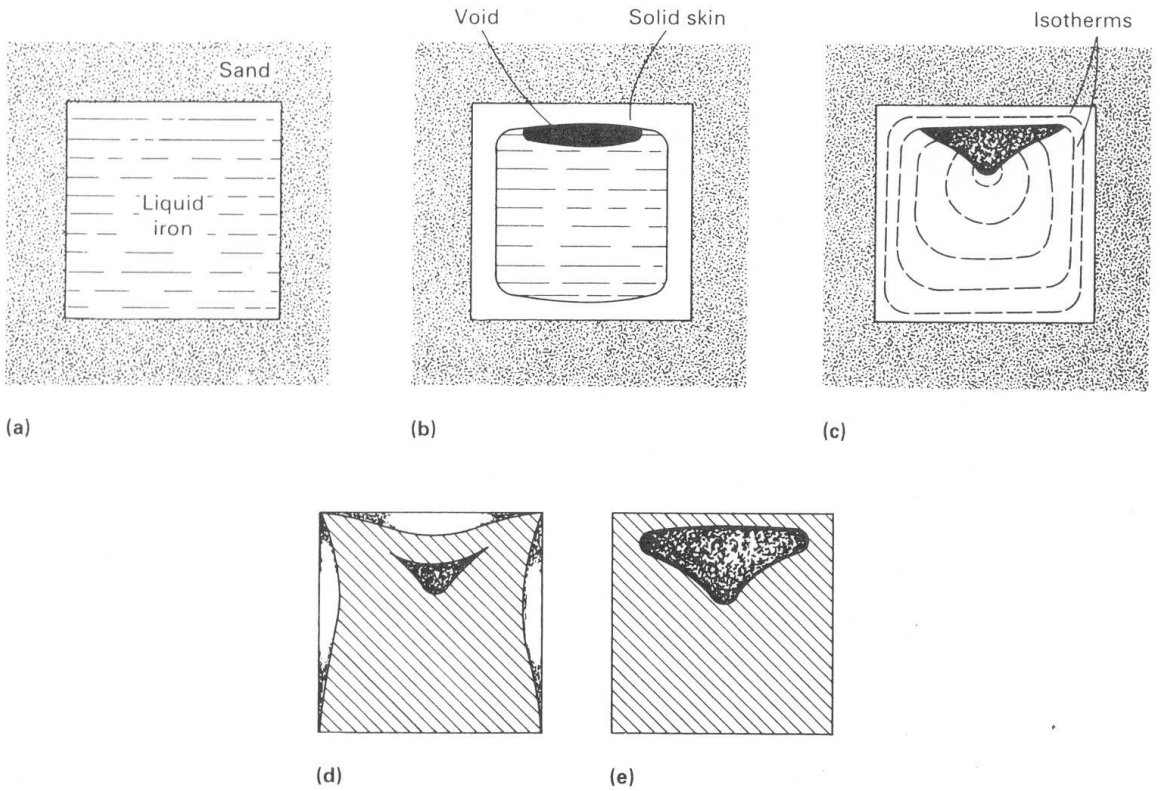



**Fig. 2** Schematic of sequence of solidification shrinkage in an iron cube. (a) Initial liquid metal. (b) Solid skin and formation of shrinkage void. (c) Internal shrinkage. (d) Internal shrinkage plus dishing. (e) Surface puncture

# Contração na solidificação

| *Metal* | *Crystal structure* | *Melting point* °C | *Liquid density* (kg/m$^3$) | *Solid density* (kg/m$^3$) | *Volume change* (%) | *Ref.* |
|---|---|---|---|---|---|---|
| Al | fcc | 660 | 2368 | 2550 | 7.14 | 1 |
| Au | fcc | 1063 | 17 380 | 18 280 | 5.47 | 1 |
| Co | fcc | 1495 | 7750 | 8180 | 5.26 | 1 |
| Cu | fcc | 1083 | 7938 | 8382 | 5.30 | 1 |
| Ni | fcc | 1453 | 7790 | 8210 | 5.11 | 1 |
| Pb | fcc | 327 | 10 665 | 11 020 | 3.22 | 1 |
| Fe | bcc | 1536 | 7035 | 7265 | 3.16 | 1 |
| Li | bcc | 181 | 528 | – | 2.74 | 4,5 |
| Na | bcc | 97 | 927 | – | 2.6 | 4,5 |
| K | bcc | 64 | 827 | – | 2.54 | 4,5 |
| Rb | bcc | 39 | 1437 | – | 2.3 | 4,5 |
| Cs | bcc | 29 | 1854 | – | 2.6 | 4,5 |
| Tl | bcc | 303 | 11 200 | – | 2.2 | 2 |
| Cd | hcp | 321 | 7998 | – | 4.00 | 2 |
| Mg | hcp | 651 | 1590 | 1655 | 4.10 | 3 |
| Zn | hcp | 420 | 6577 | – | 4.08 | 2 |
| Ce | hcp | 787 | 6668 | 6646 | −0.33 | 1 |
| In | fct | 156 | 7017 | – | 1.98 | 2 |
| Sn | tetrag | 232 | 6986 | 7166 | 2.51 | 1 |
| Bi | rhomb | 271 | 10 034 | 9701 | −3.32 | 1 |
| Sb | rhomb | 631 | 6493 | 6535 | 0.64 | 1 |
| Si | diam | 1410 | 2525 | – | −2.9 | 2 |

References: 1, Wray (1976); 2, Lucas (quoted by Wray, 1976); 3, This book; 4, Iida and Guthrie (1988); 5, Brandes (1983).

# O módulo de resfriamento

- Módulo de Resfriamento

$$MR = \frac{Volume}{Superfície}$$

- Tempo de Solidificação

$$TS = c.(MR)^n$$

  - 1,5 < n < 2
  - Exemplos:
    - Calcular p/ Esfera, Chapa, Cubo, Cilindro
    - Como maximizar MR p/ Cilindro?
    - Comparar
    - MR em geometrias mais complexas

# Massalotes

- Usados em fundidos, ou parte de fundidos, com MR elevado
- Geralmente desnecessários para fundidos de paredes finas (< 6 mm)
- $MR_m > 1{,}2.MR_f$

# Massalotes

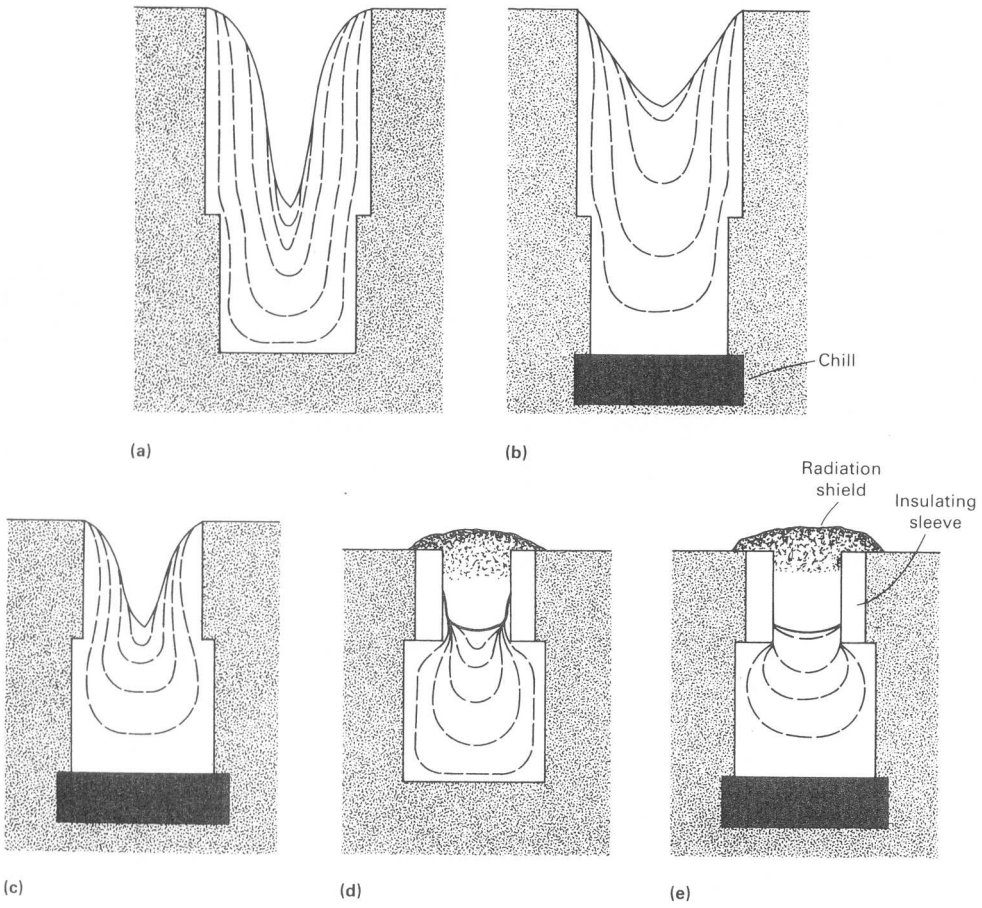



**Fig. 3** Methods of controlling shrinkage in an iron cube to reduce riser size. (a) Open-top riser. (b) Open-top riser plus chill. (c) Small open-top riser plus chill. (d) Insulated riser. (e) Insulated riser plus chill

# Eficiência de massalotes

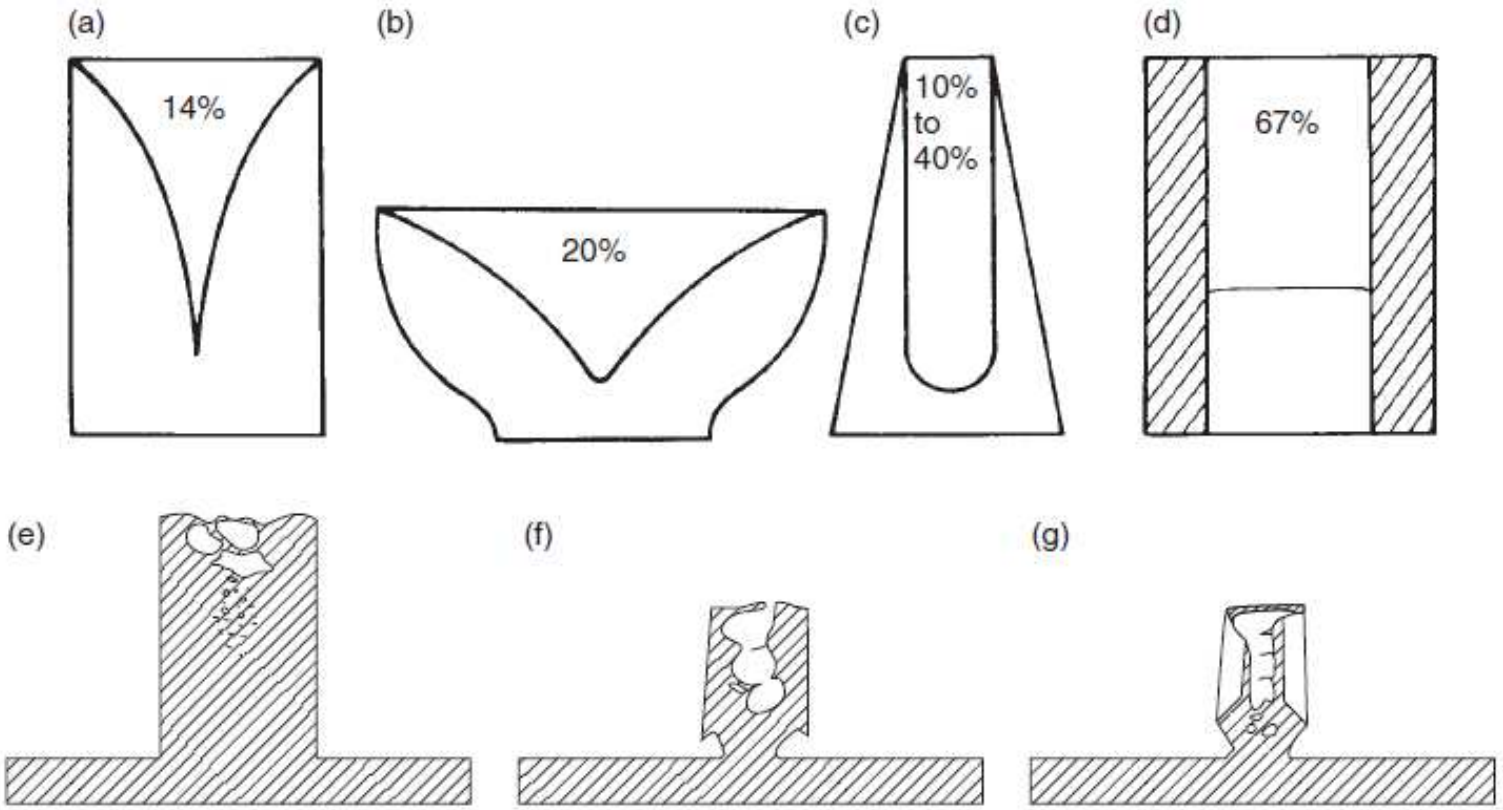



**Figure 6.5** *Metal utilization of feeders of various forms moulded in sand. The (a) cylindrical and (b) hemispherical heads have been treated with normal feeding compounds; (c) efficiency of the reverse taper heads depends on detailed geometry (Heine, 1982, 1983); (d) exothermic sleeve (Beeley, 1972). Metal utilization for ductile iron plates with (e) cylindrical sand feeder; (f) insulating feeder; and (g) cruciform exothermic feeder (after Foseco 1988).*

# Volume do Massalote

- $V_m = \alpha.V_p/(e-\alpha)$

- Exemplos para massalote cilíndrico com H=1,5D (e=14%):
  - Ligas de Al: $V_m = V_p$
  - Aços: $V_m = 0,4\ V_p$

# Posicionamento de massalotes

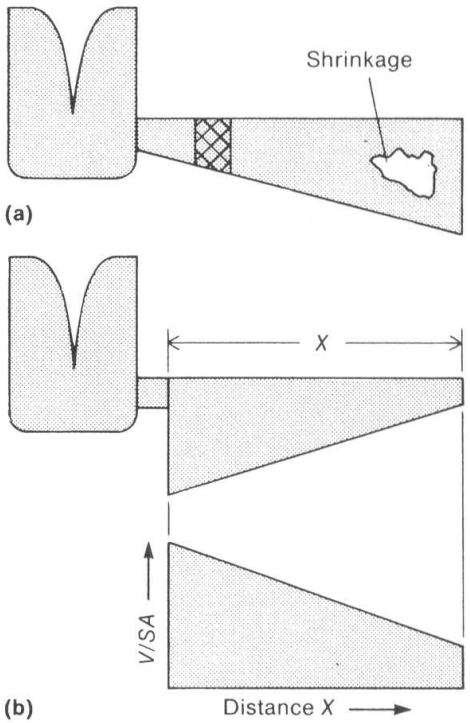



**Fig. 3** Casting design and solidification of a simple wedge. (a) Riser placed at narrow end of wedge; shrinkage occurs at wide end. The crosshatched region represents the approximate area of the casting where solidification is first complete, thus cutting off the feeding path of the casting. (b) Correct riser placement. *V/SA* is the volume-to-surface-area ratio (casting modulus).

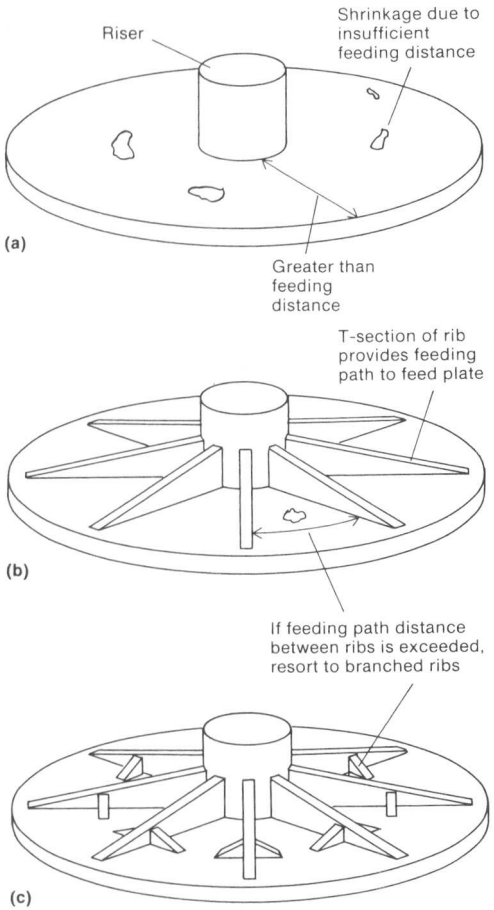
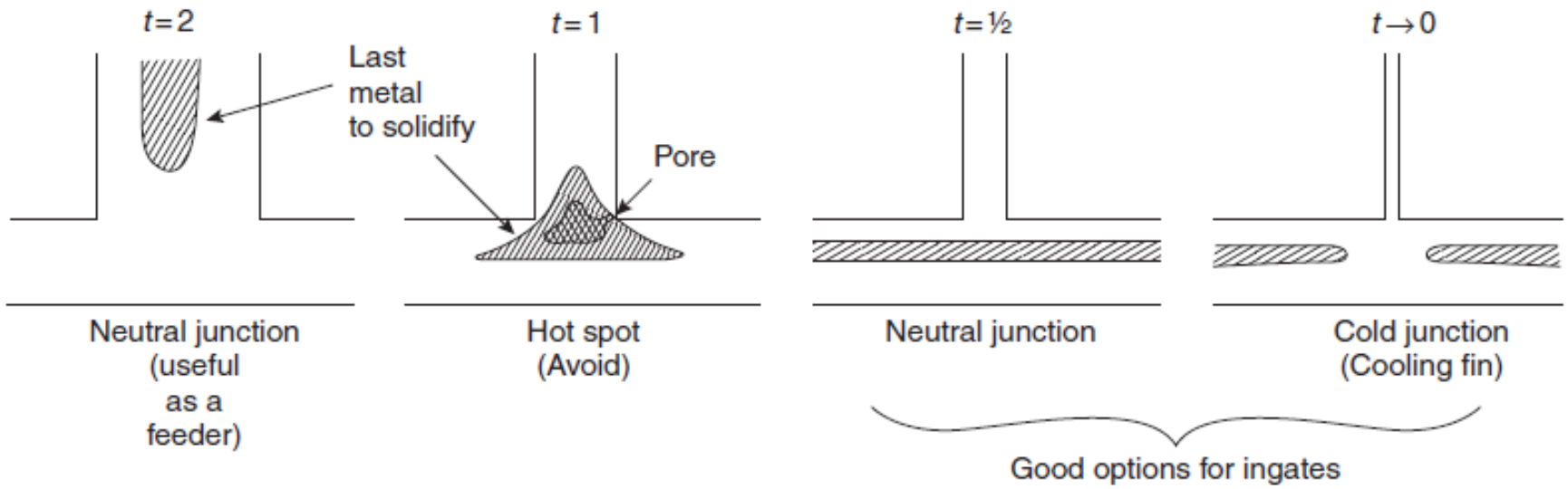


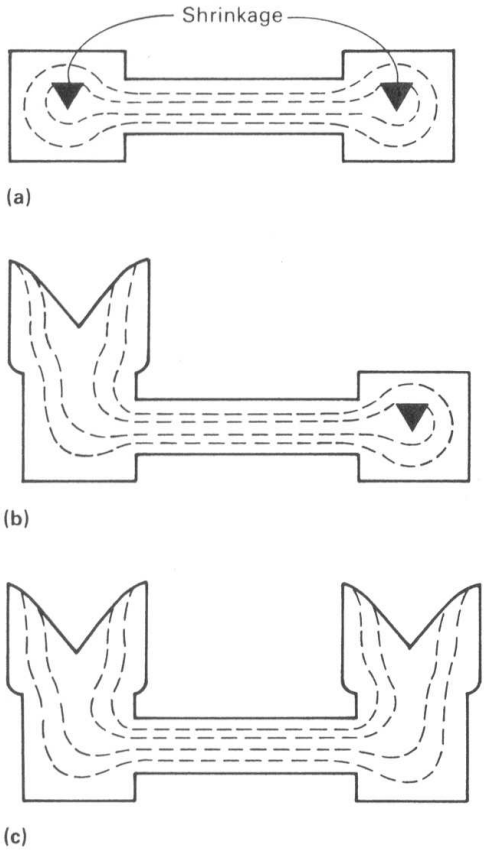

**Fig. 16** Feeding path design considerations. (a) Circular flat plate with a single riser. (b) Addition of wedge-shaped ribs to ensure proper solidification. (c) Branched ribs to overcome feeding problems at the circumference of the plate

# Ligação do massalote à peça




t = razão entre as espessuras

# Posicionamento de Massalotes
## (direcionando a solidificação)



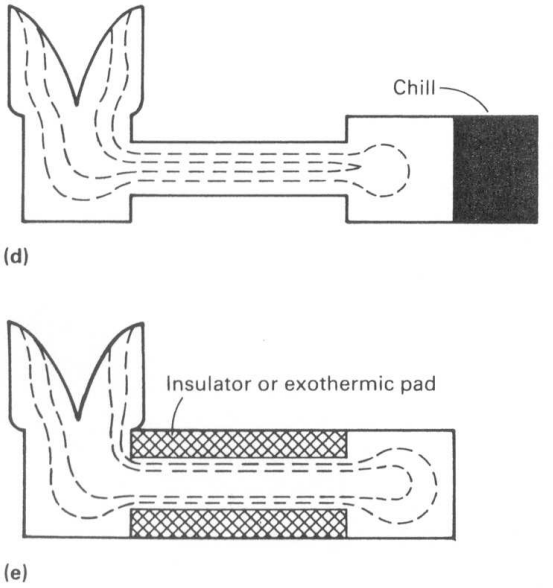
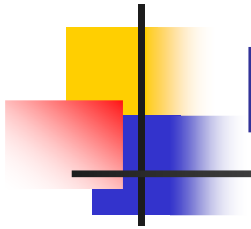



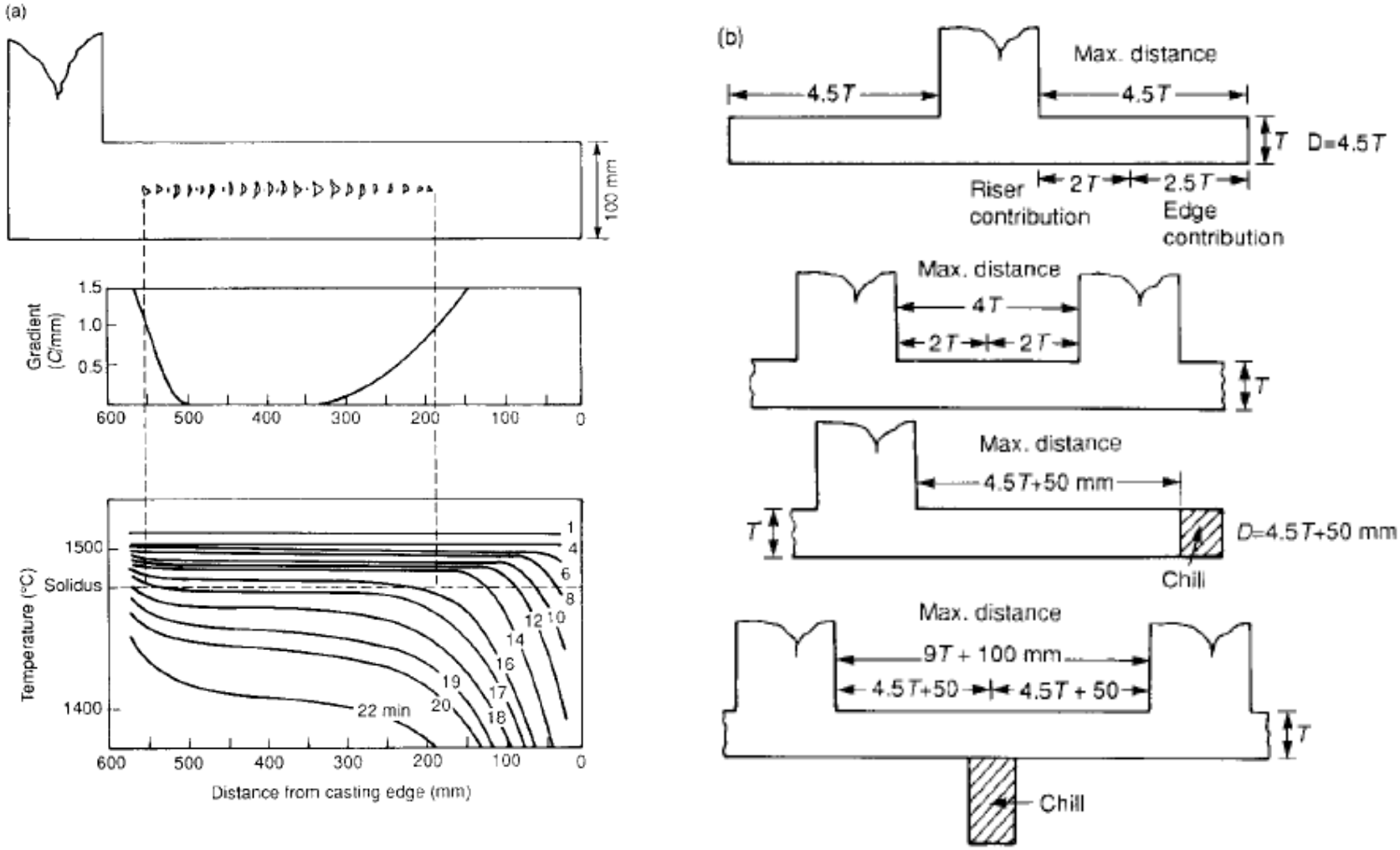

**Fig. 16** Risering of isolated heavy sections joined by a thinner section to minimize shrinkage and number of risers. (a) Workpiece with no risers. (b) Riser added to one side. (c) Risers located on both ends. (d) Chill applied to one end and riser to other end. (e) Riser used on one end and insulator or exothermic pad on opposite end



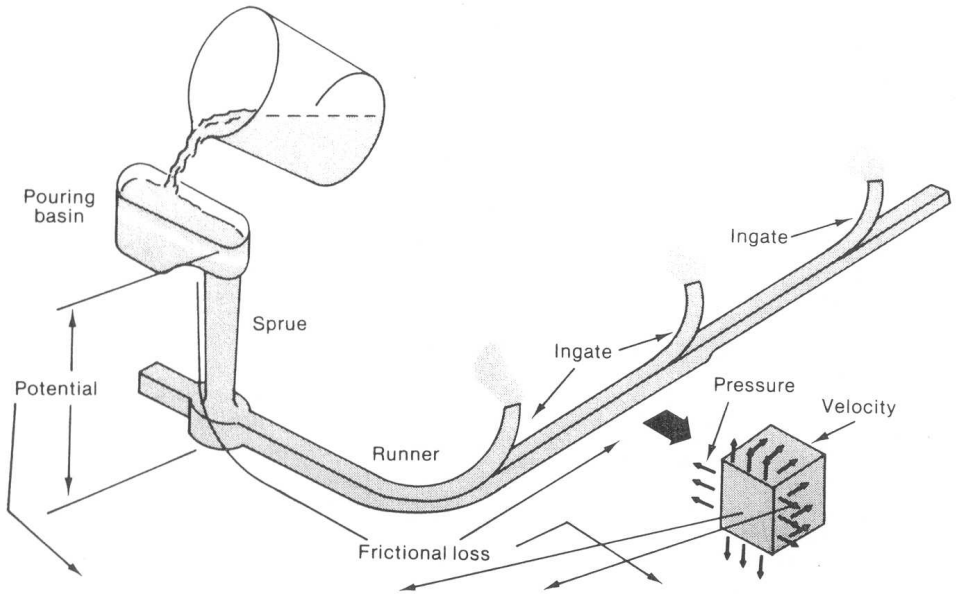
# Exemplos

- Simulações em Excel

# Mais de um massalote



# Sistema de preenchimento



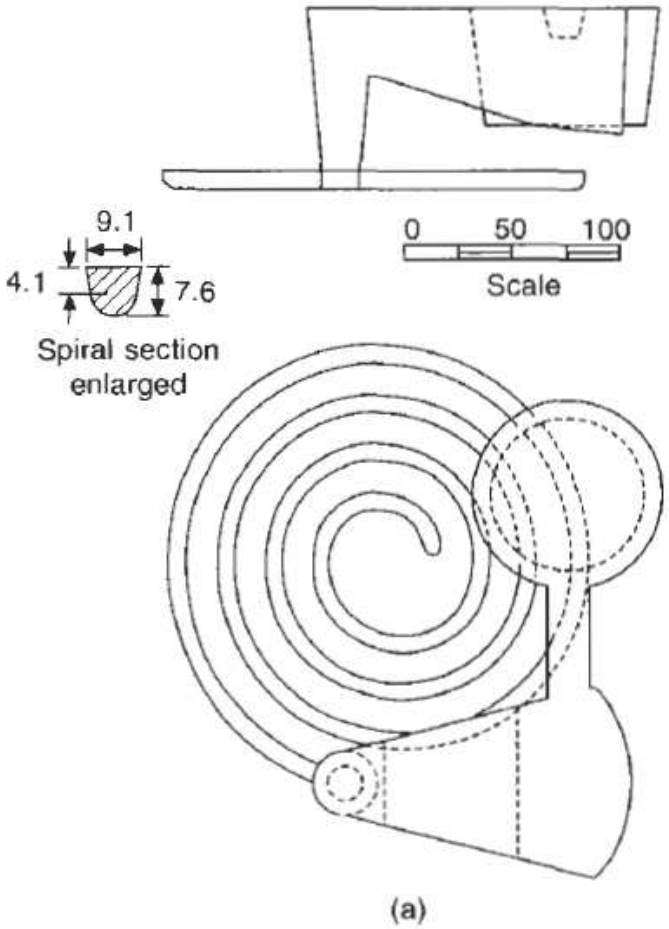

Potential head ($wZ$) + Pressure head ($wPv$) + Velocity head ($wV^2/2g$) + Friction loss of head ($wF$) = Constant ($K$)

**Fig. 2** Schematic illustrating the application of Bernoulli's theorem to a gating system. Source: Ref 1

Principal função:

- **Evitar turbulência superficial**
  - Manter avanço contínuo da superfície líquida
  - Evitar efeito "cascata" e a incorporação de bolhas
  - Controlar a velocidade e evitar projeção de metal

# Medidas de fluidez



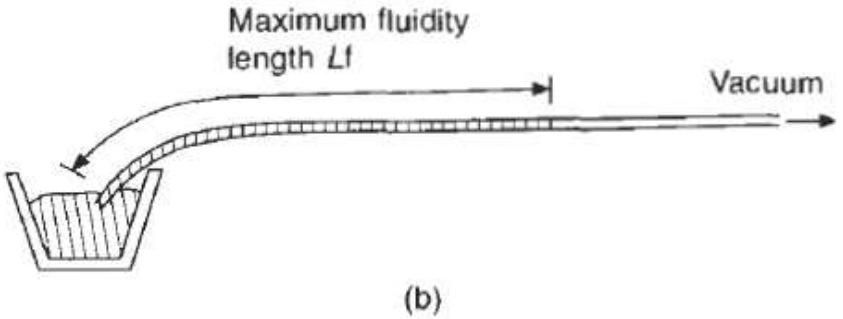




**Figure 3.2** *Typical fluidity tests for (a) foundry and (b) laboratory use.*

# Influência do tipo de liga na fluidez do metal

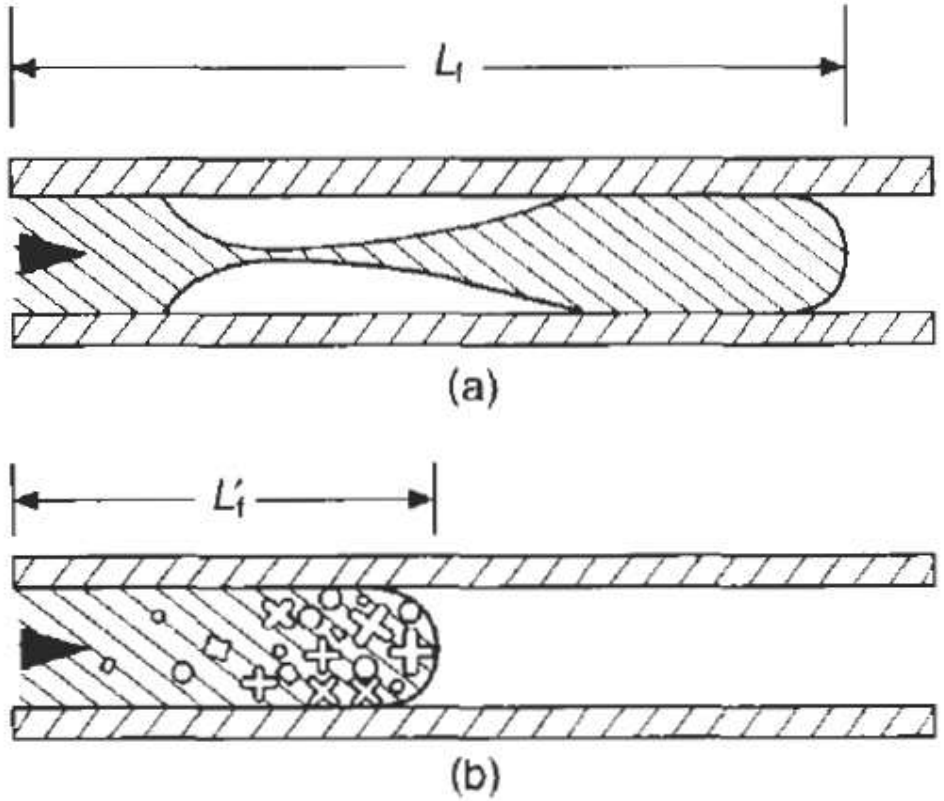
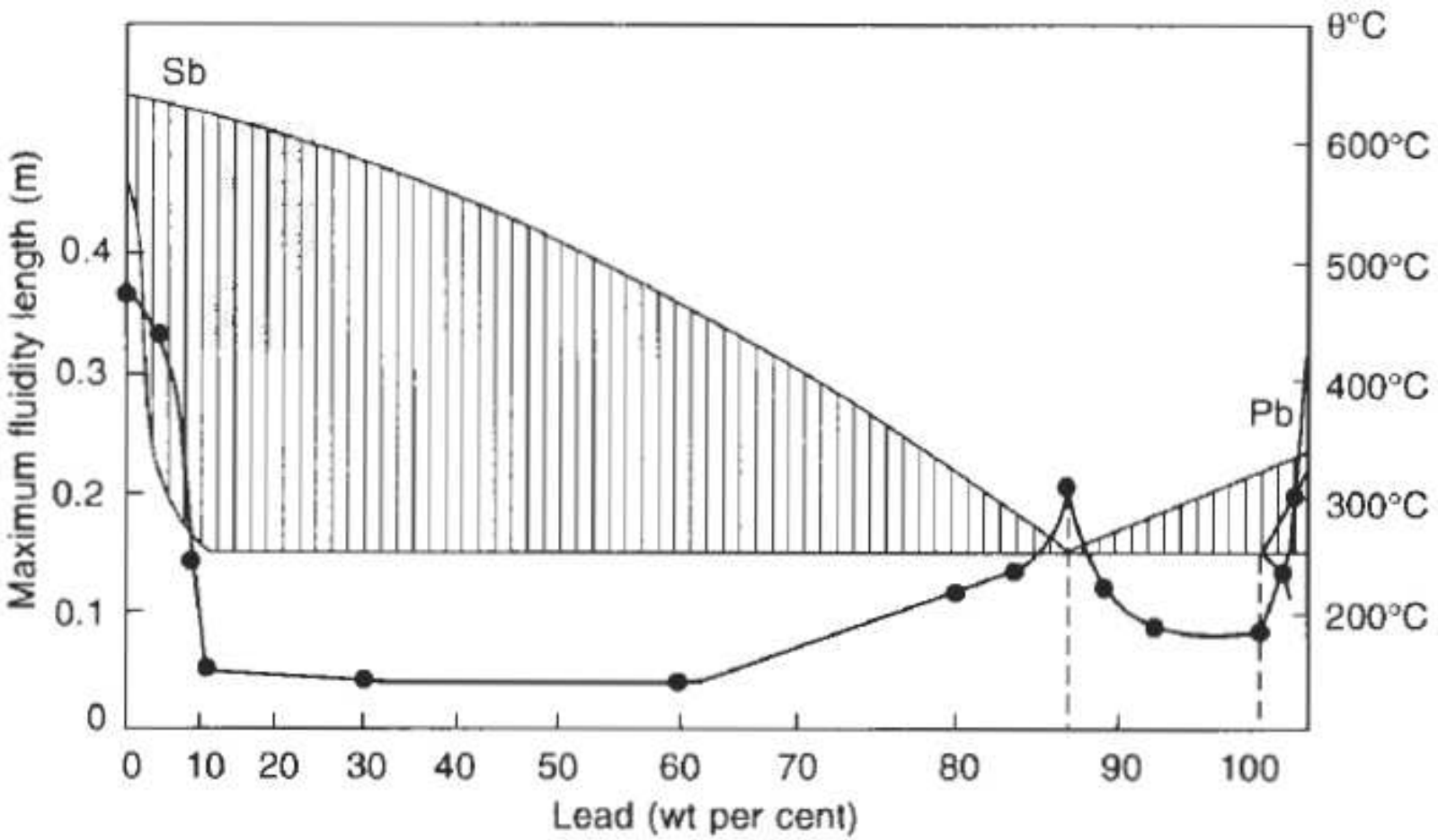
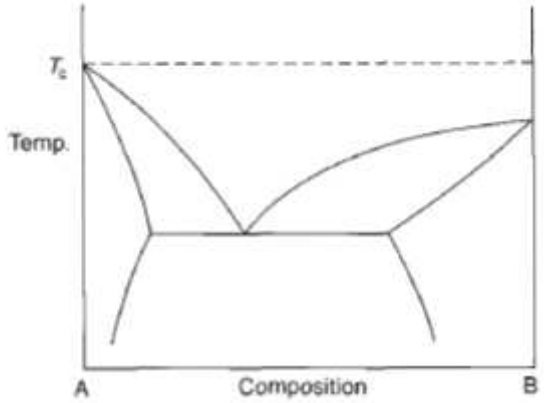


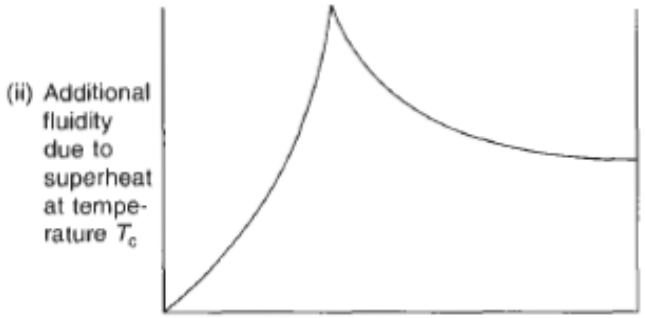

**Figure 3.3** *Flow arrest: (a) in pure metals by complete solidification; and (b) in long-freezing-range alloys by partial solidification.*

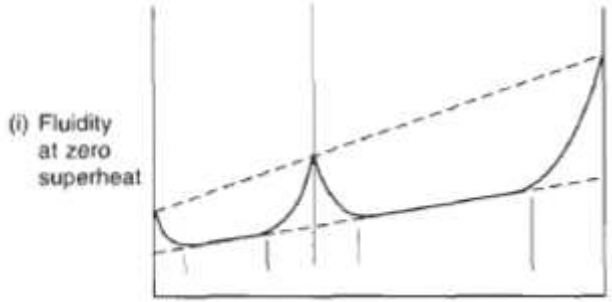
# Fluidez de acordo com o intervalo de solidificação

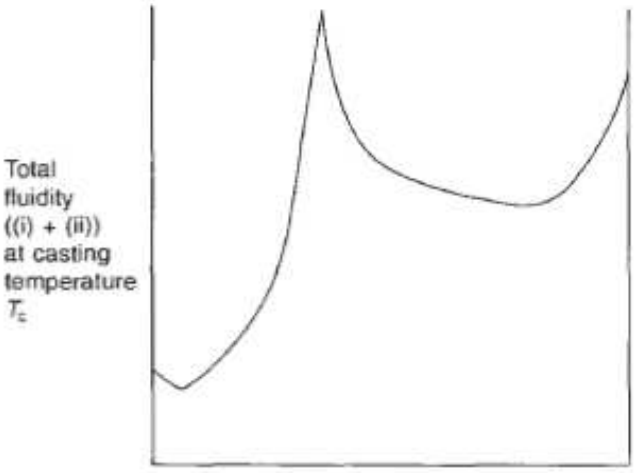


# Influência do super-aquecimento



# Efeito de um avanço turbulento na superfície do metal líquido

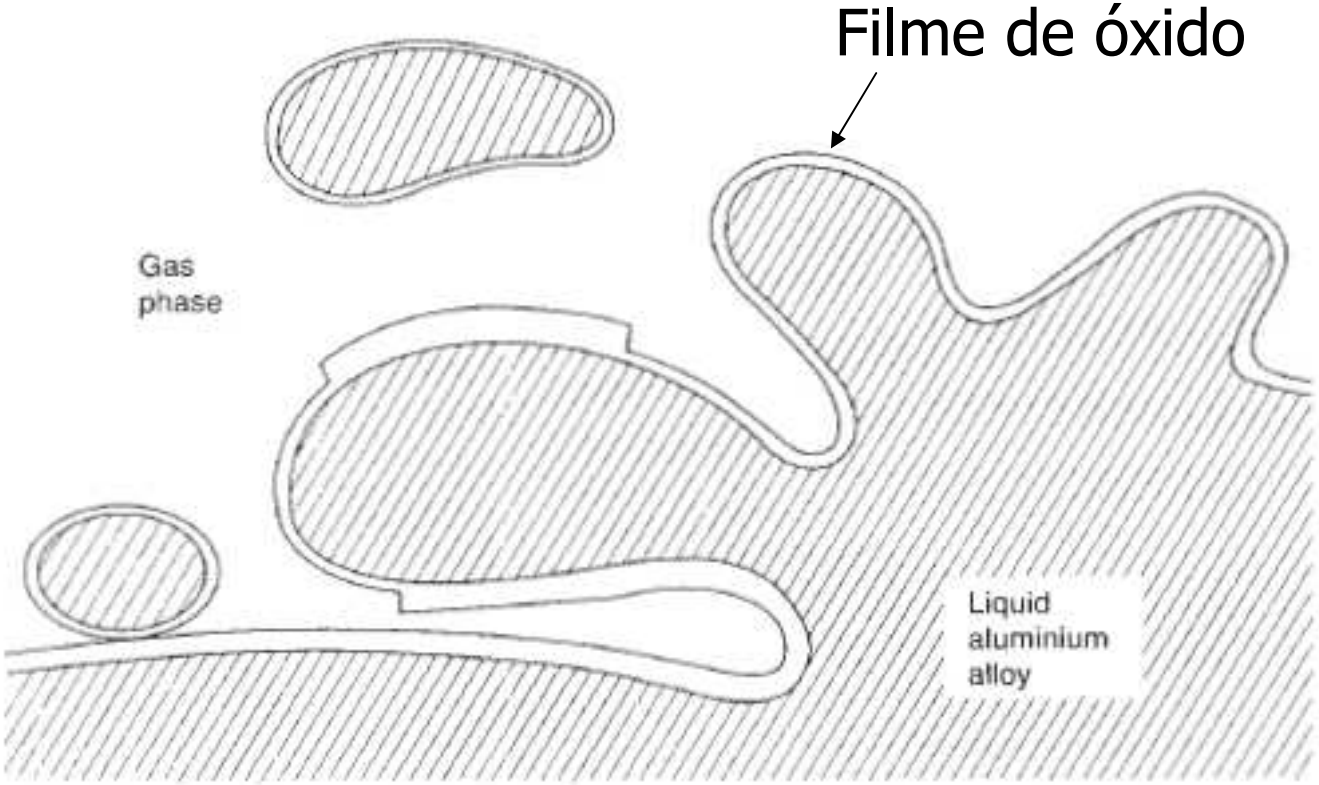
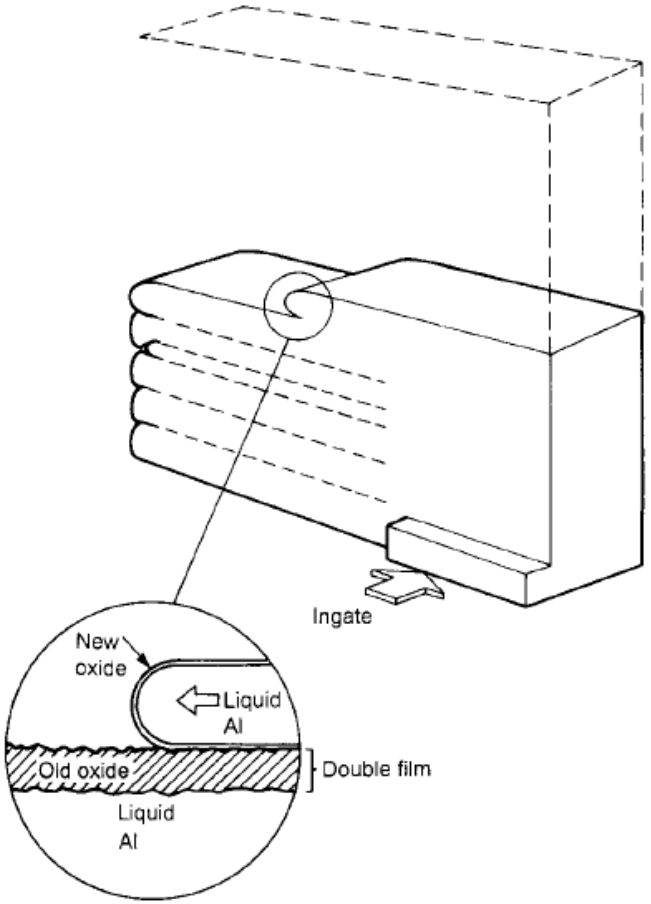



**Figure 2.1** *Sketch of a surface entrainment event.*

# Efeitos de alimentação intermitente



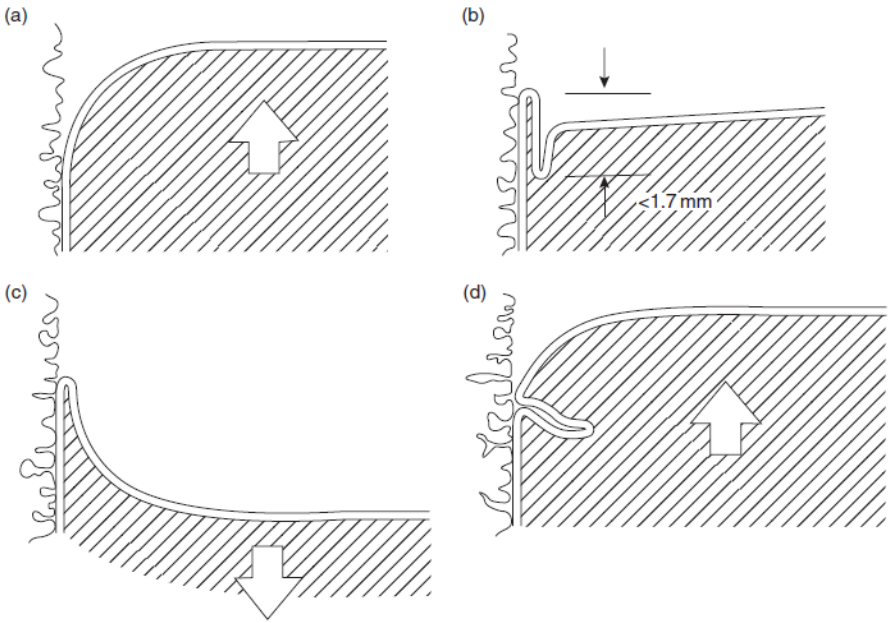
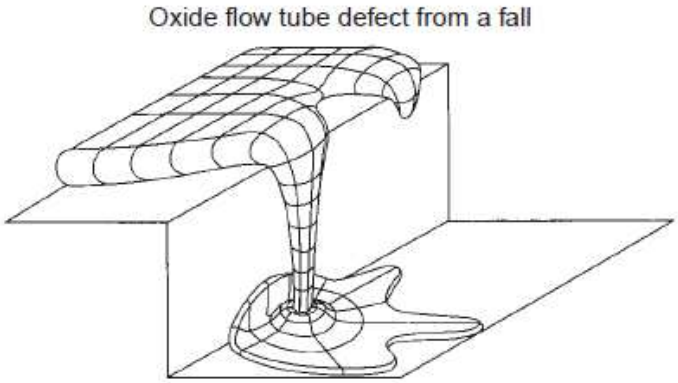




**Figure 3.6** *The creation of a bifilm crack by the reversal of the front, causing the meniscus to flatten and enfold in the excess surface area. Surface cracks of the order of a millimetre depth can be formed in this way.*

# Efeito "cascata" e projeção de metal líquido




Projeção

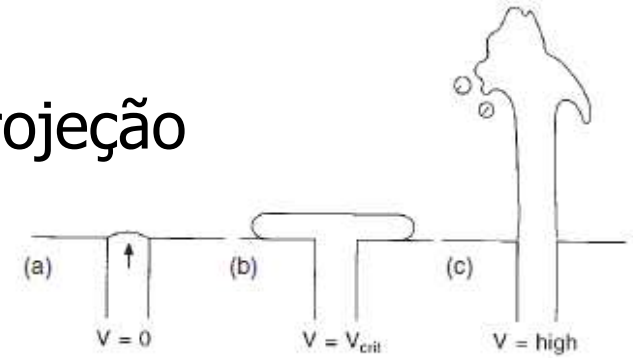
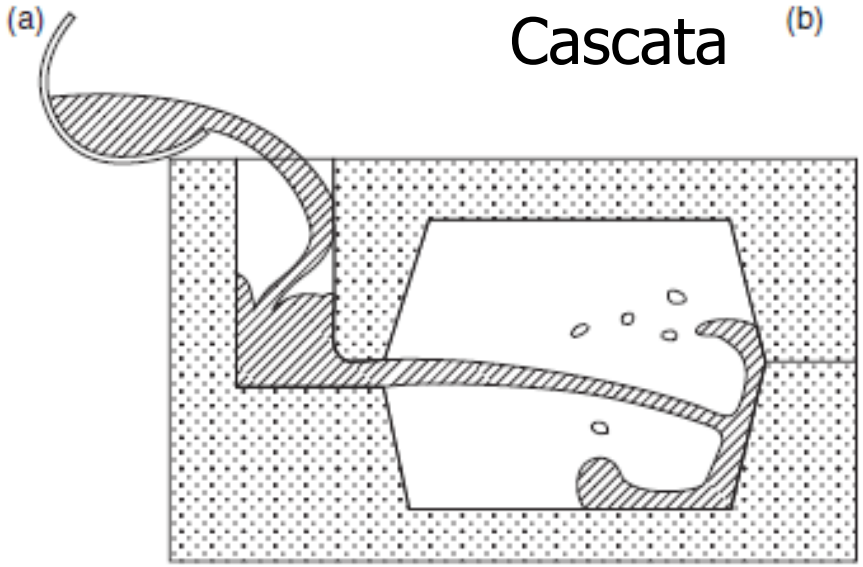
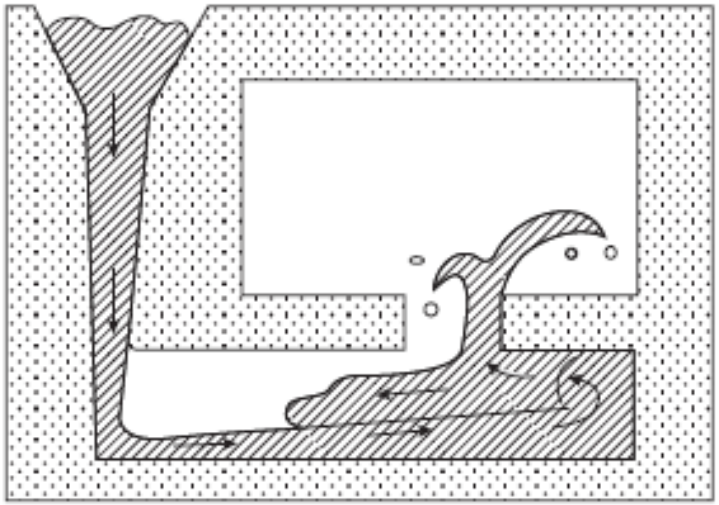



**Figure 2.1** *The extremes of velocity entering the mould from the gate; zero, critical and high.*

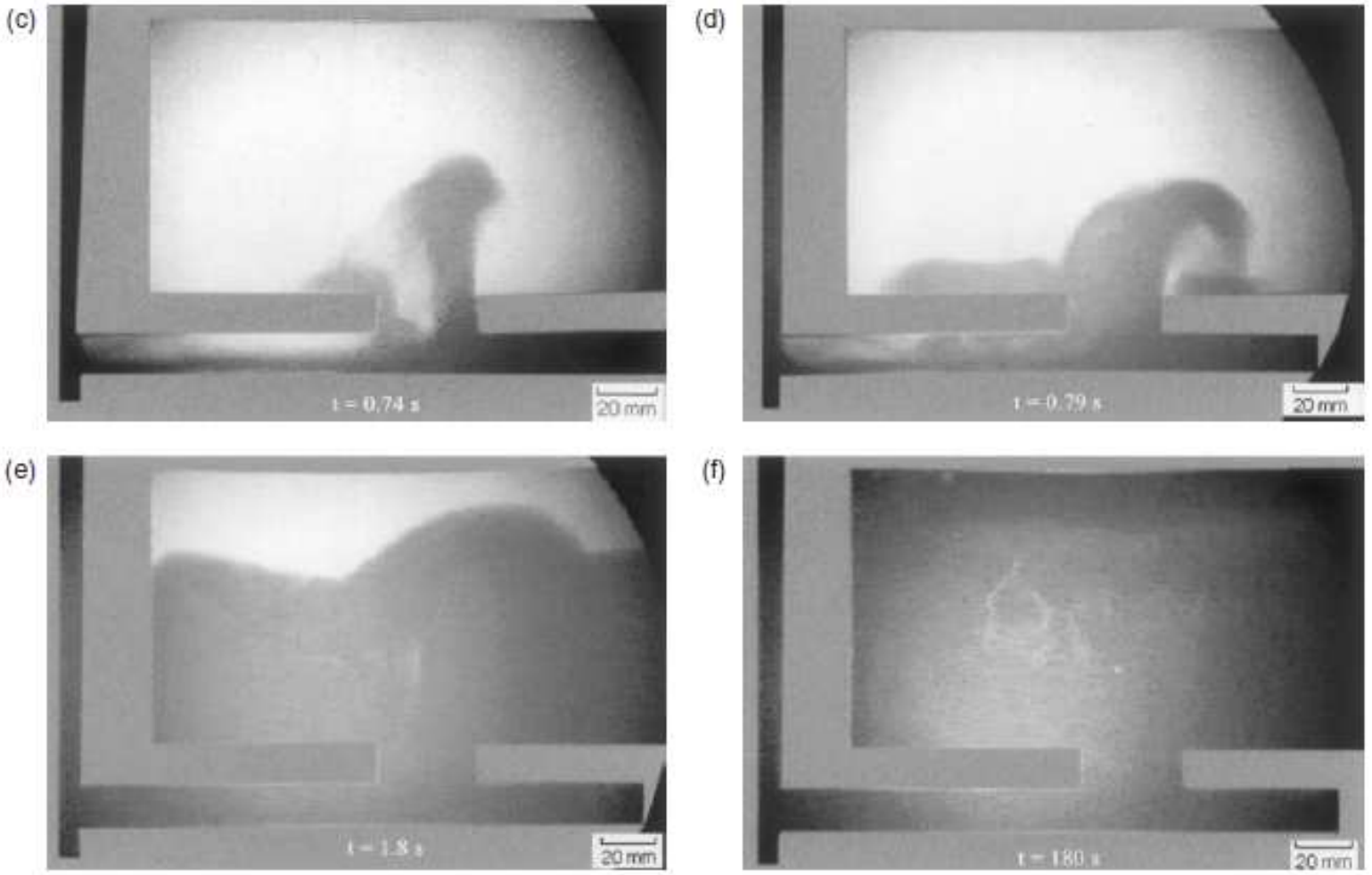
$V_{crit}$ ≈ 0,5 m/s p/ a maioria dos metais

Cascata



# Efeito da projeção de metal líquido



# Efeito de mudanças bruscas de área durante o preenchimento

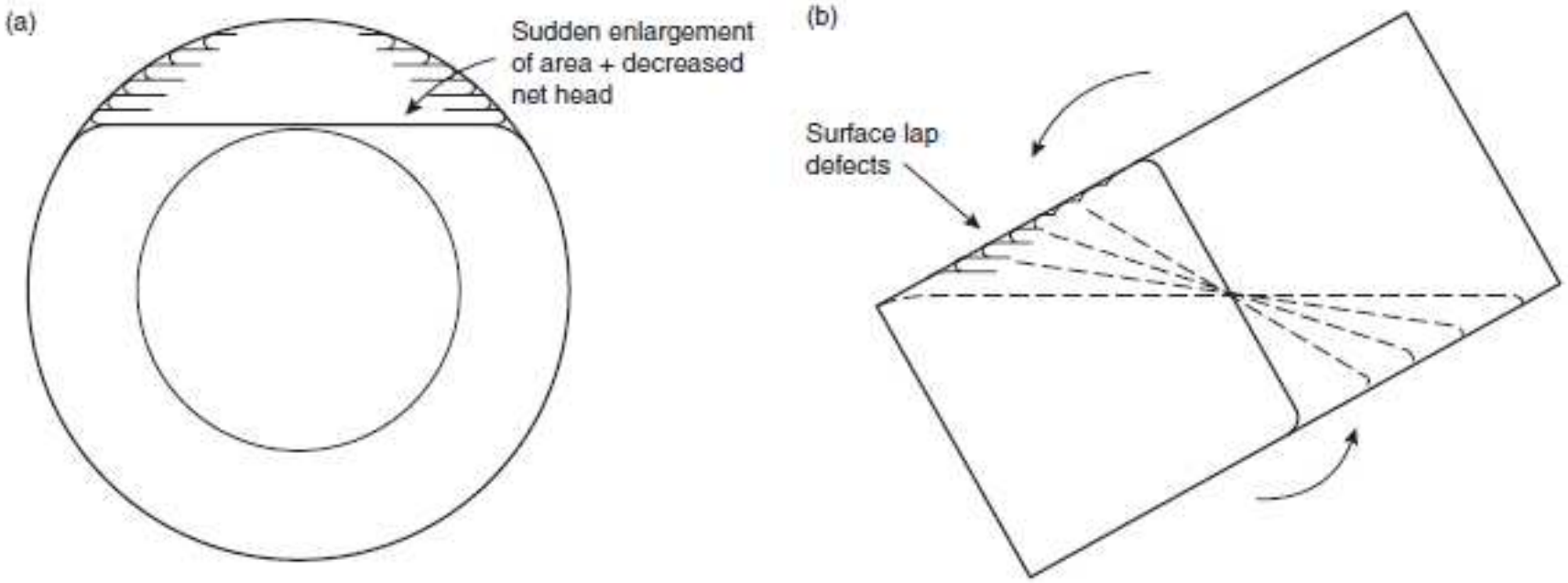



**Figure 2.60** *Common lap problems at low rates of rise of liquid surface in the mould (a) in a horizontal pipe or cylinder; (b) on the cope surface of a tilt casting.*

# Efeito de mudanças bruscas de área durante o preenchimento

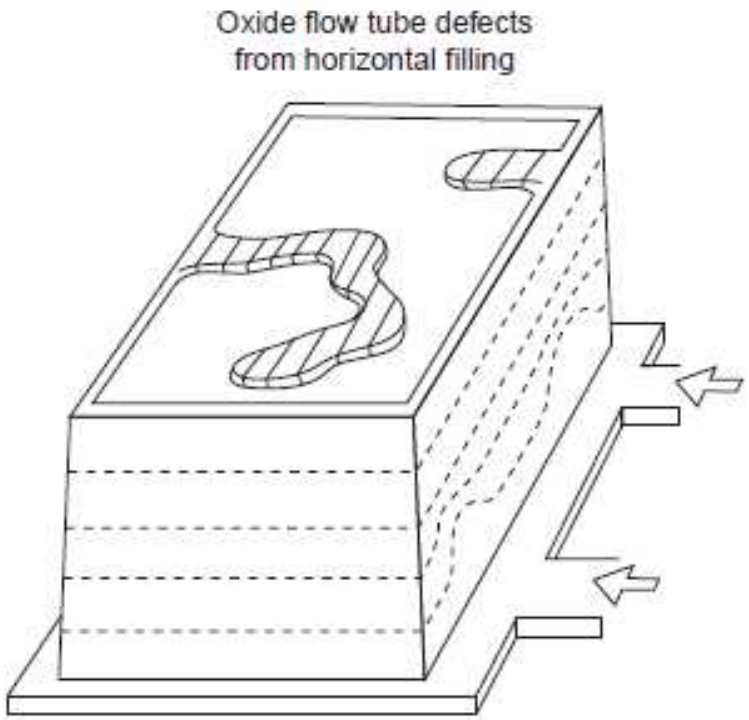



**Figure 3.4** *The filling of a rectangular box type casting, illustrating the progressive advance of the front that characterizes the filling of vertical walls. The horizontal top, however, fills unpredictable meanders of river-like flows, leading to horizontal oxide flow tubes.*

# Inclusão de bolhas devido a sistema de alimentação incorreto

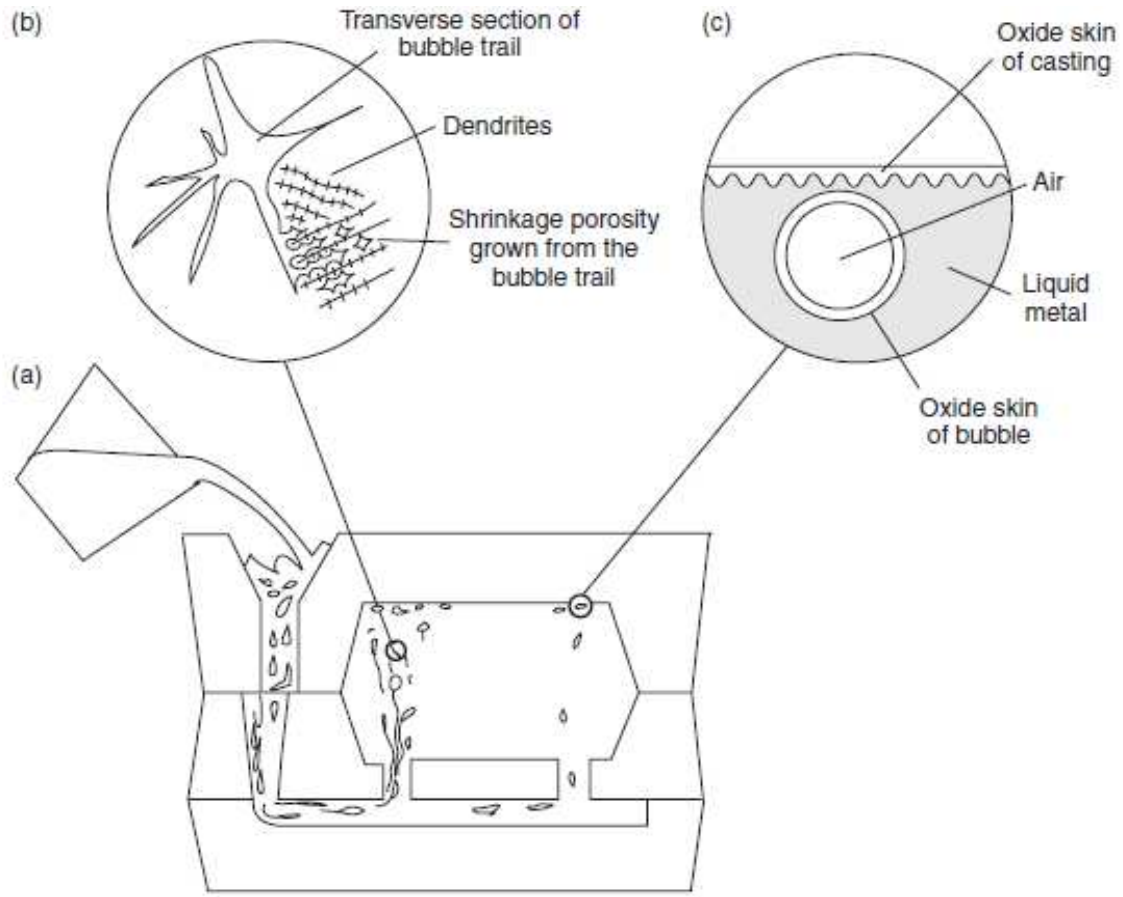
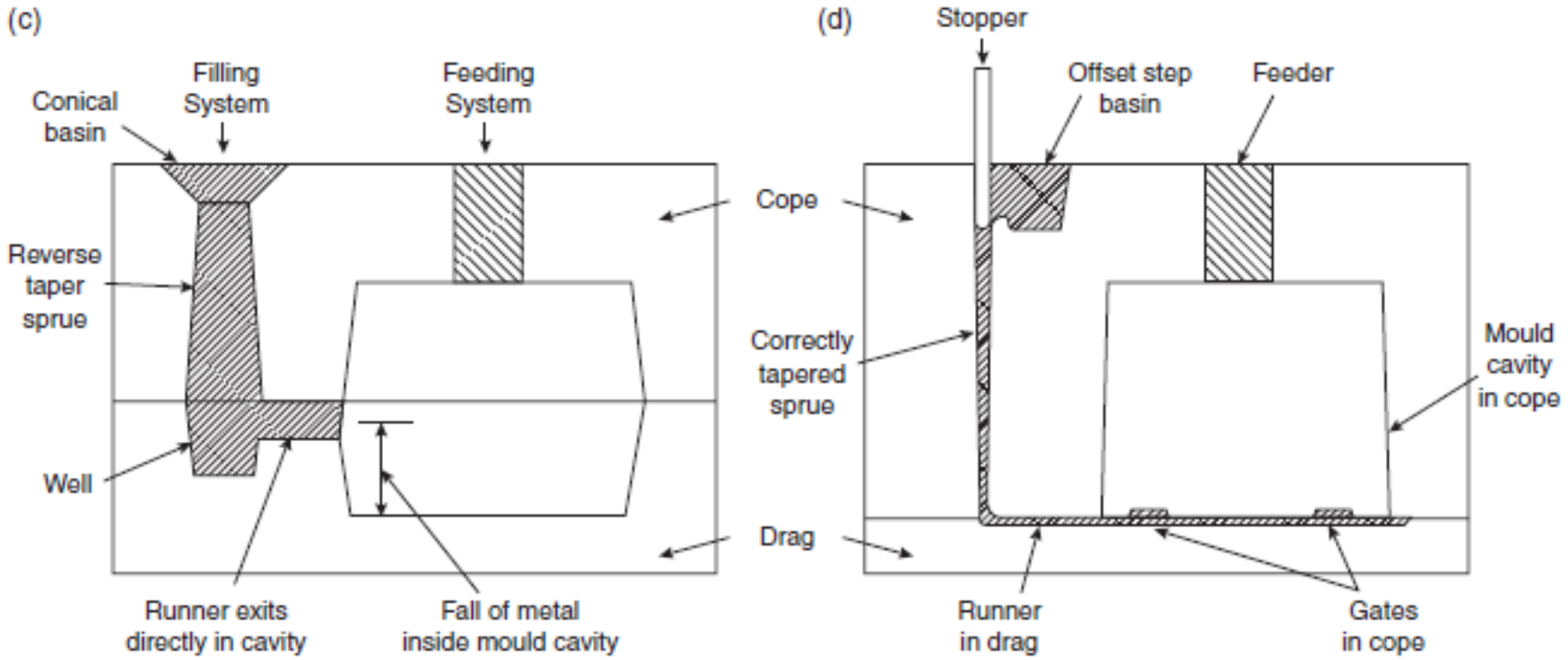


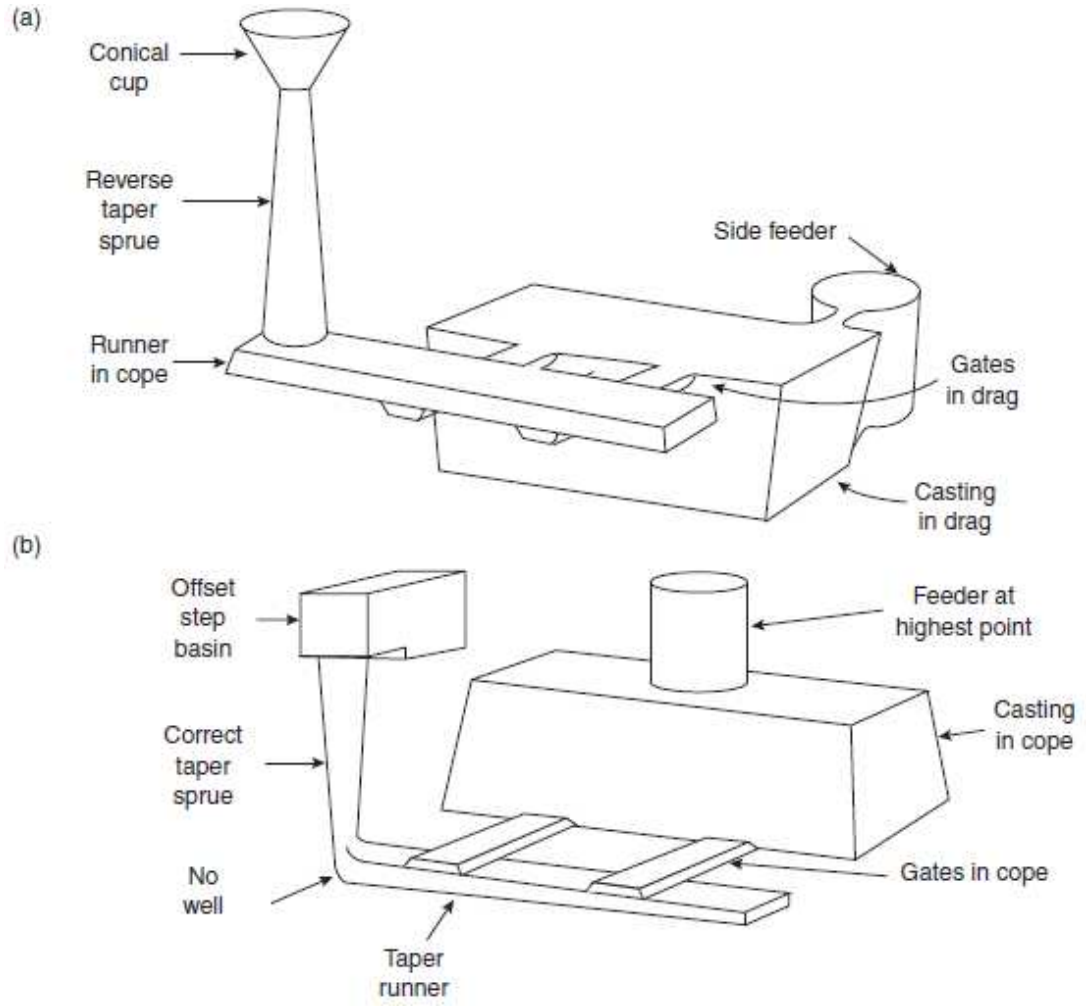

**Figure 4.1** *(a) Pattern of bubble damage in a casting; (b) trails invisible in radiography are usually visible on transverse sections; (c) small entrained air bubbles do not have sufficient buoyancy to break the double oxide barrier to escape to the atmosphere.*

# Exemplo




**Ruim** **Bom**

# Exemplo




**Ruim**

**Bom**

# Bacia de vazamento

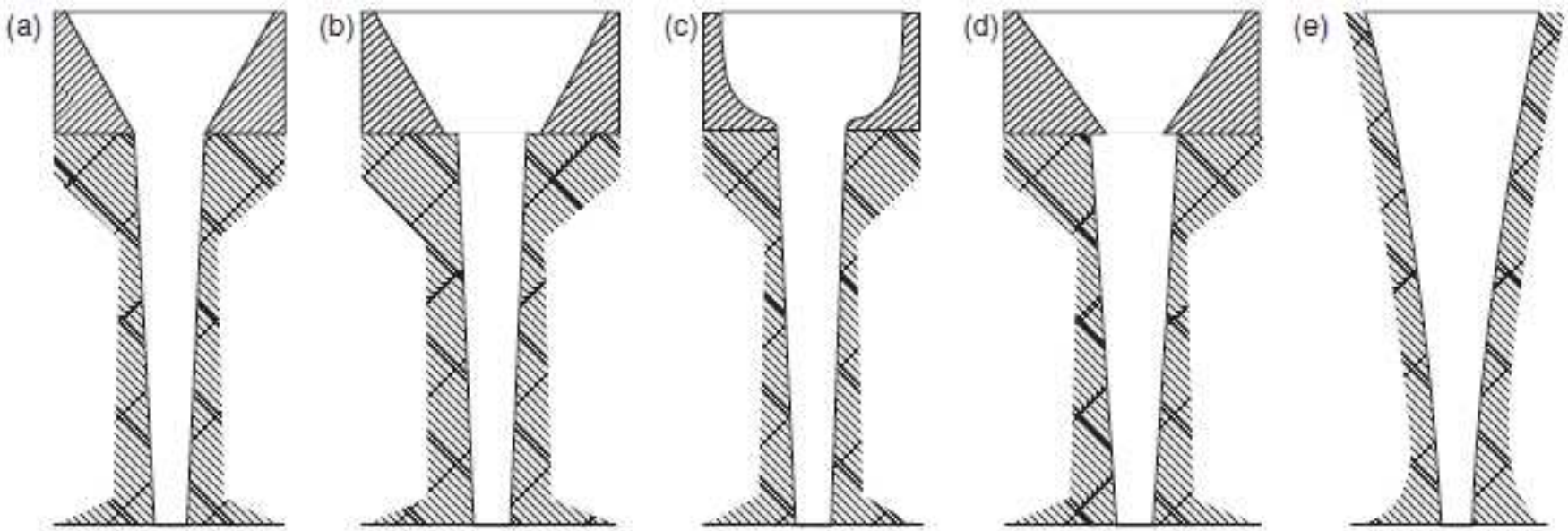



**Figure 2.8** *A rogues gallery of non-recommended scrap generating systems. Conical basin and sprue combinations showing (a) perhaps least damaging; (b) basin too large; (c) cup form; (d) basin too small; (e) enlarged sprue to act as a combined basin and sprue.*

TODOS OS CASOS ACIMA NÃO SÃO RECOMENDADOS

# Bacia de vazamento

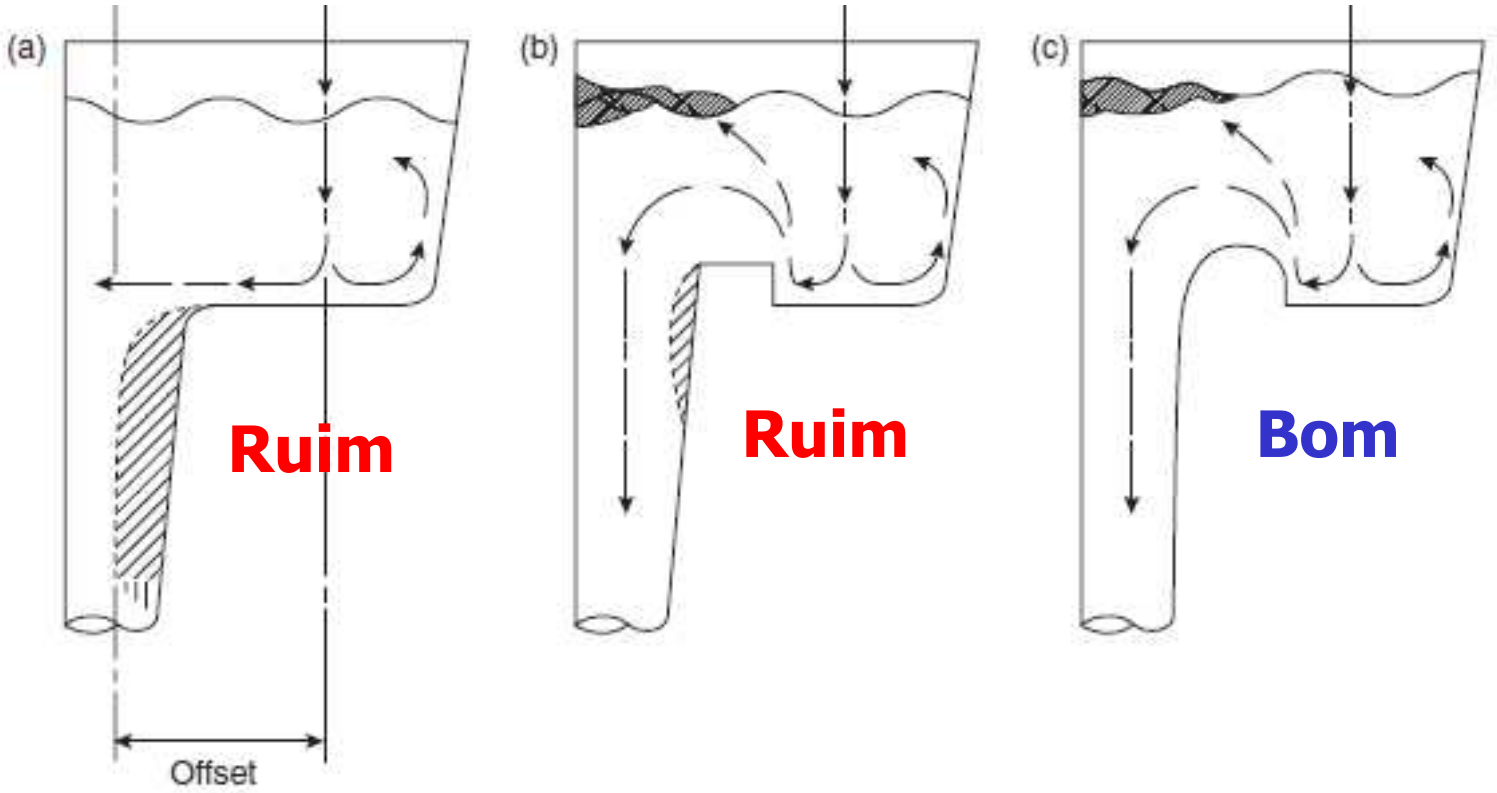



**Figure 2.9** *Offset pouring basins (a) without step (definitely not recommended); (b) sharp step (not recommended); (c) radiused step (recommended).*

# Bacia de vazamento

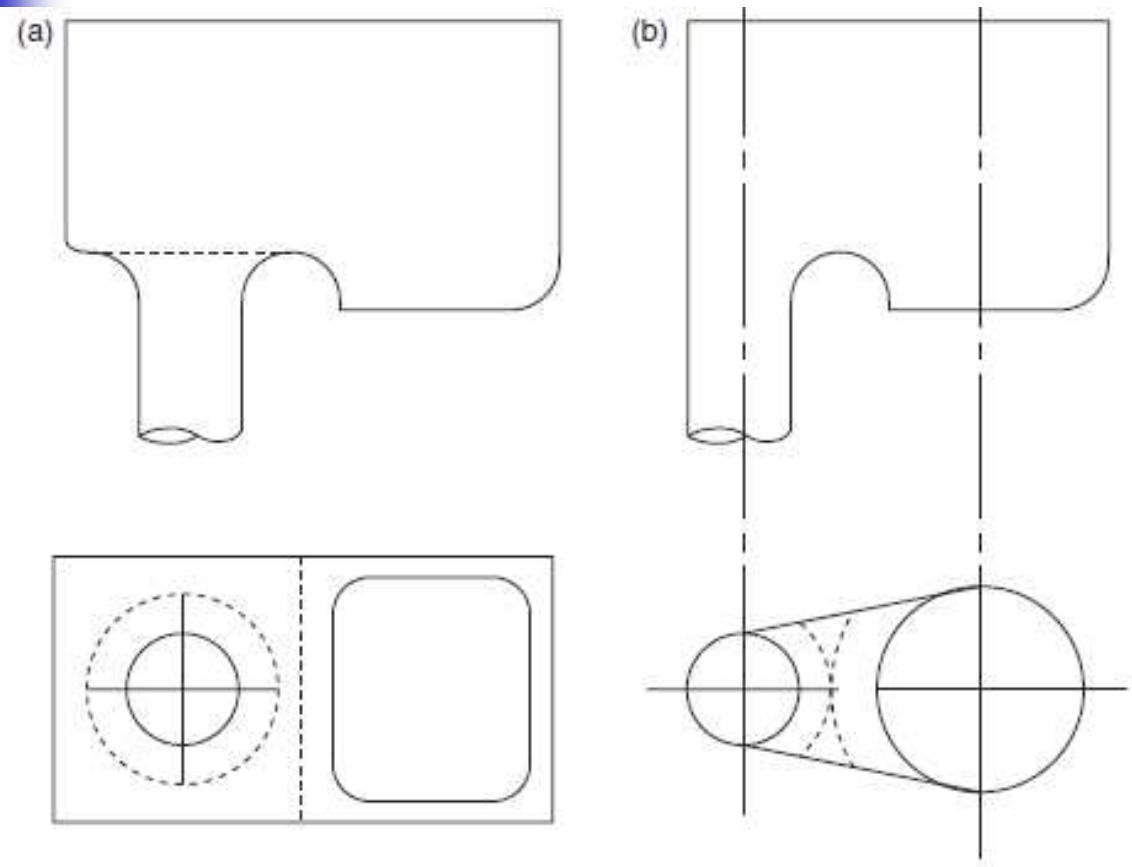



**Figure 2.11** *Side and plan views of offset basins (a) conventional rectangular; (b) slimmed shape to streamline flow and improve metal yield.*

**Melhor**

# Canal de descida

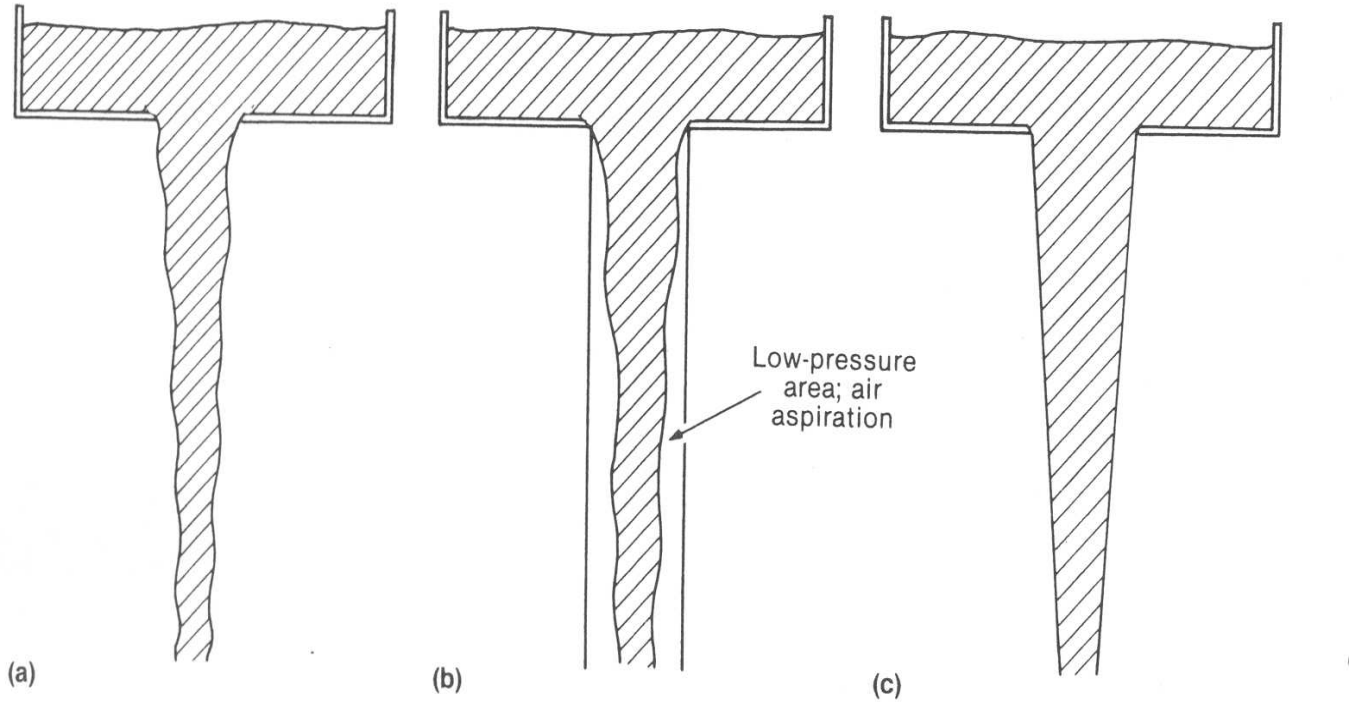



**Fig. 3** Schematic showing the advantages of a tapered sprue over a straight-sided sprue. (a) Natural flow of a free-falling liquid. (b) Air aspiration induced by liquid flow in a straight-sided sprue. (c) Liquid flow in a tapered sprue

# Canal de descida

$$\frac{A_1}{A_2} = \sqrt{\frac{H_2}{H_1}}$$

$$t = \frac{V}{A_2.C.\sqrt{2gH_2}}$$

t – tempo de preenchimento estimado (alimentação por baixo)
V – volume de metal
C – eficiência do canal (C=1 p/ atrito zero)

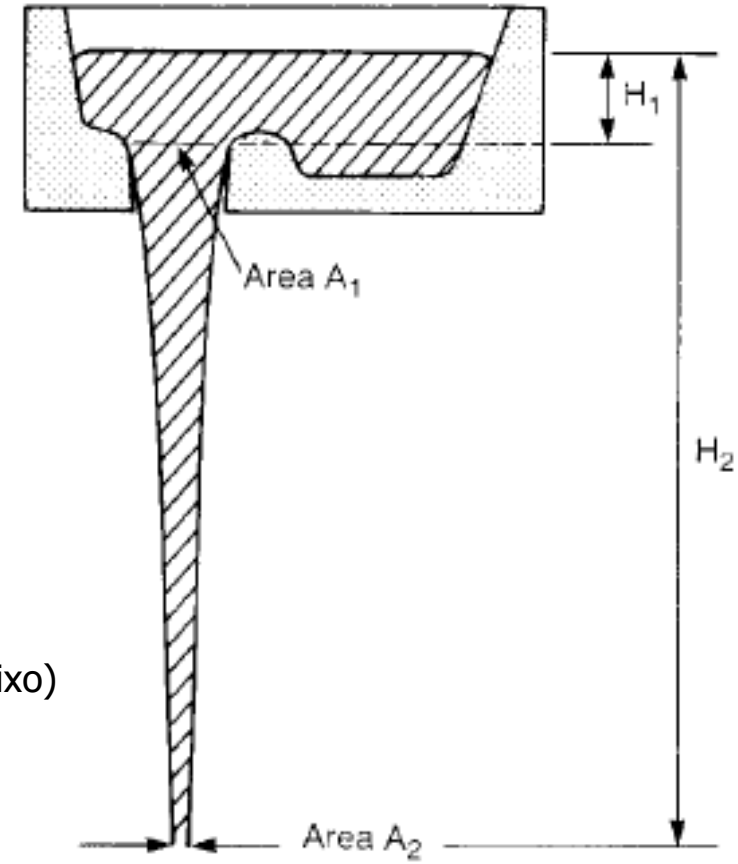



**Figure 2.13** *The geometry of the stream falling freely from a basin.*

# O canal de descida e a curva do filete de metal líquido

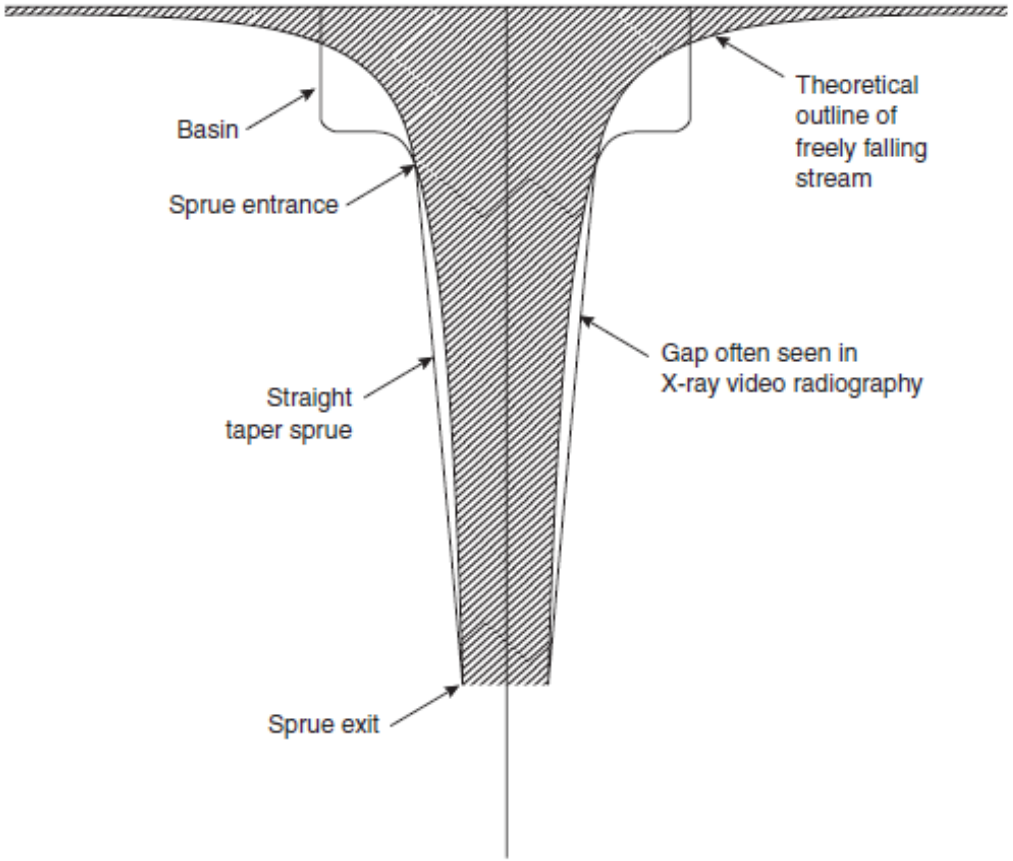
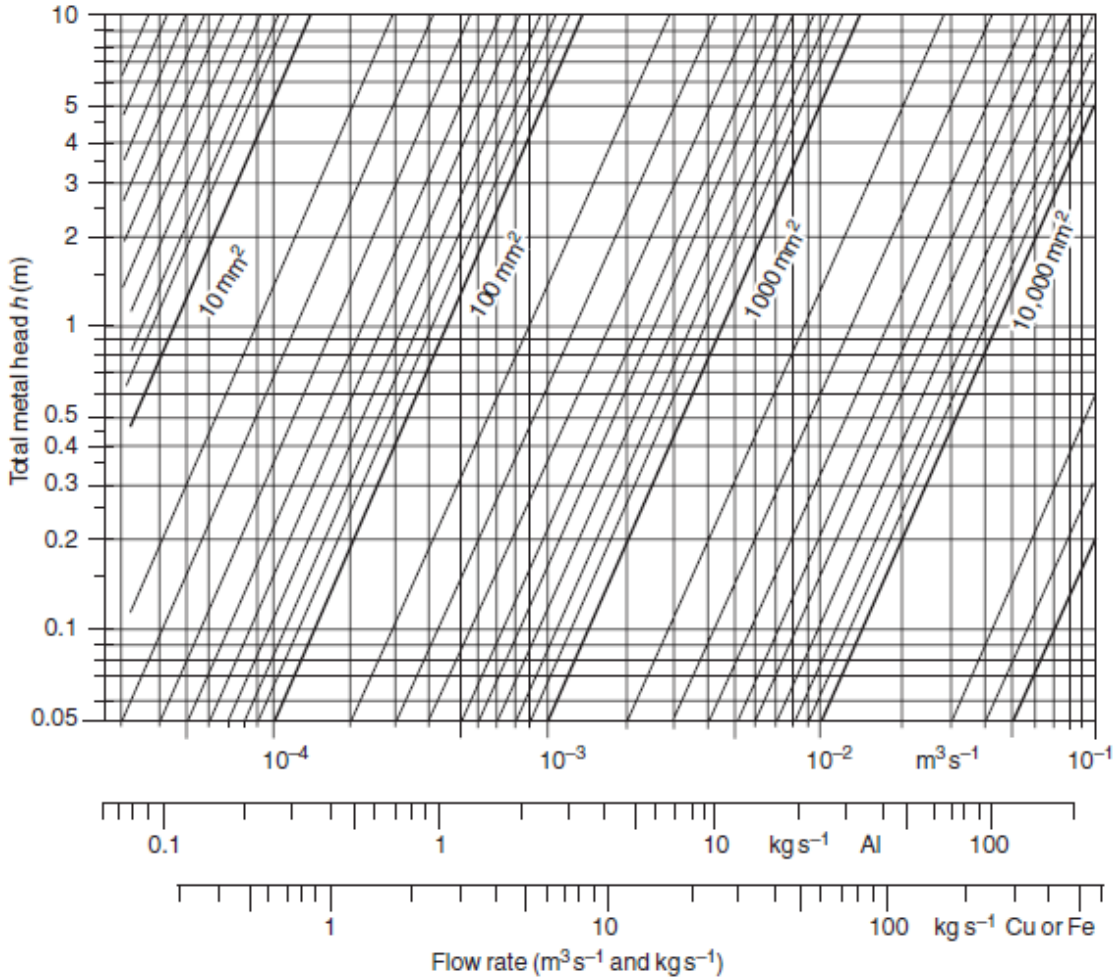



**Figure 2.15** *The theoretical hyperbola shape of the falling stream, illustrating the complicating effects of the basin and sprue entrance.*

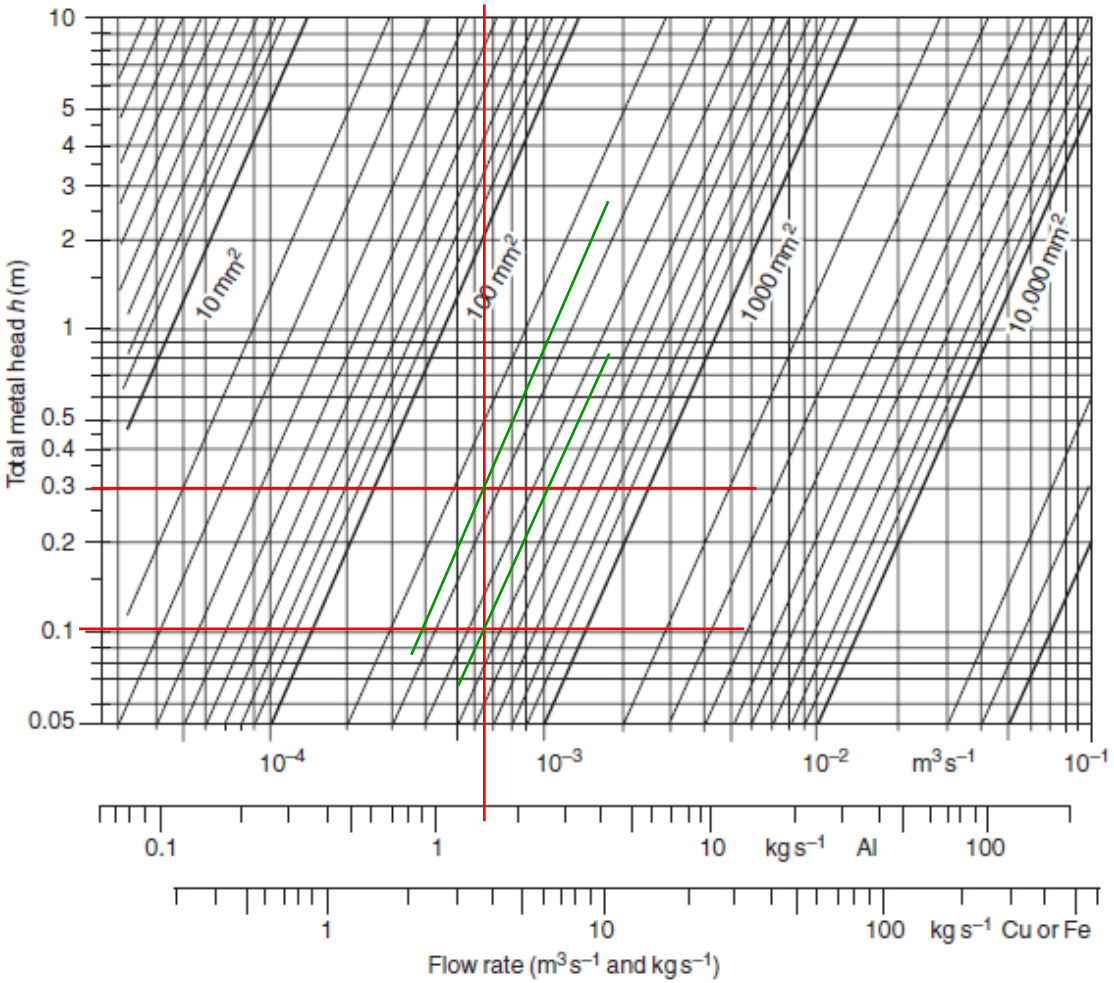
# Diagrama de áreas para canais de descida



# Exemplo de uso

- Liga de Al
- Taxa de alimentação média: 1,0 Kg/s
- Usar taxa inicial 1,5x maior: 1,5 Kg/s
- H1 = 100 mm
- H2 = 300 mm

# Exemplo de uso




A1 ≈ 450 mm²
A2 ≈ 250 mm²

Usar 1,2.A1
para compensar
erro da geometria

Portanto:
A1 ≈ 540 mm²

# Base do canal de descida

**Ruim** **Ruim** **Ruim** **Bom** **Bom**

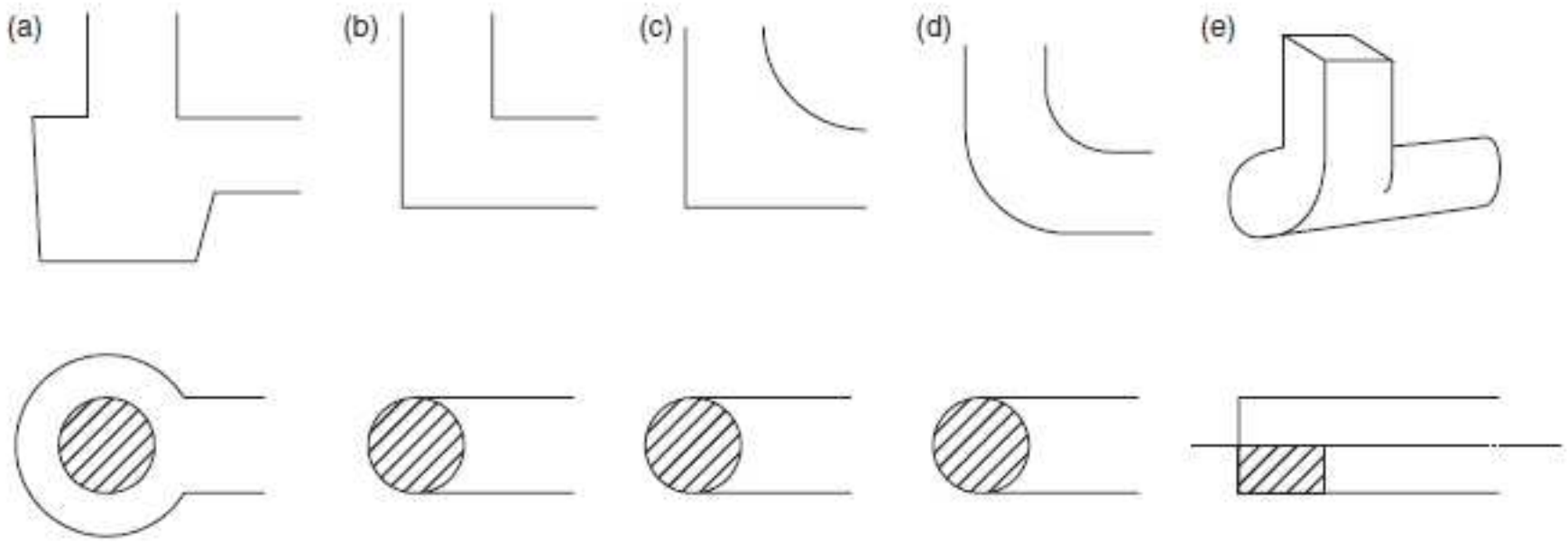



**Figure 2.19** *A variety of sprue/runner junctions in side and plan views from poorest (a) to best (d). The offset junction at (e) forms a vortex flow along the cylindrical runner.*

# Base do canal de descida

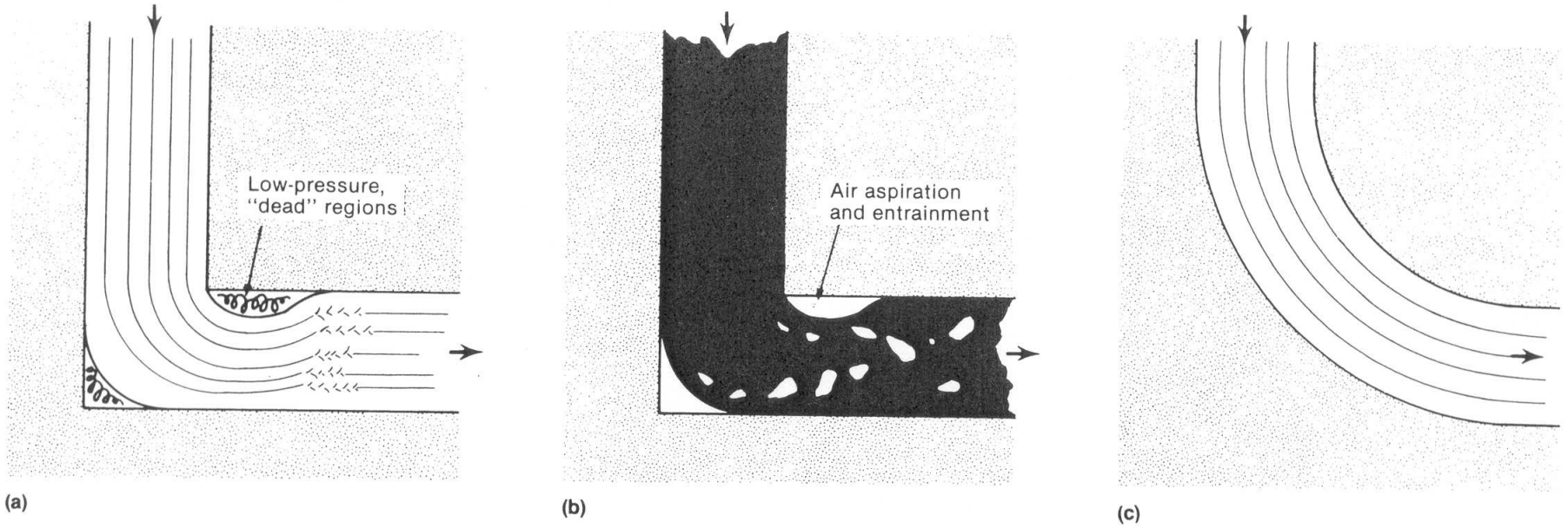



**Fig. 7** Schematic illustrating fluid flow around right-angle and curved bends in a gating system. (a) Turbulence resulting from a sharp corner. (b) Metal damage resulting from a sharp corner. (c) Streamlined corner that minimizes turbulence and metal damage

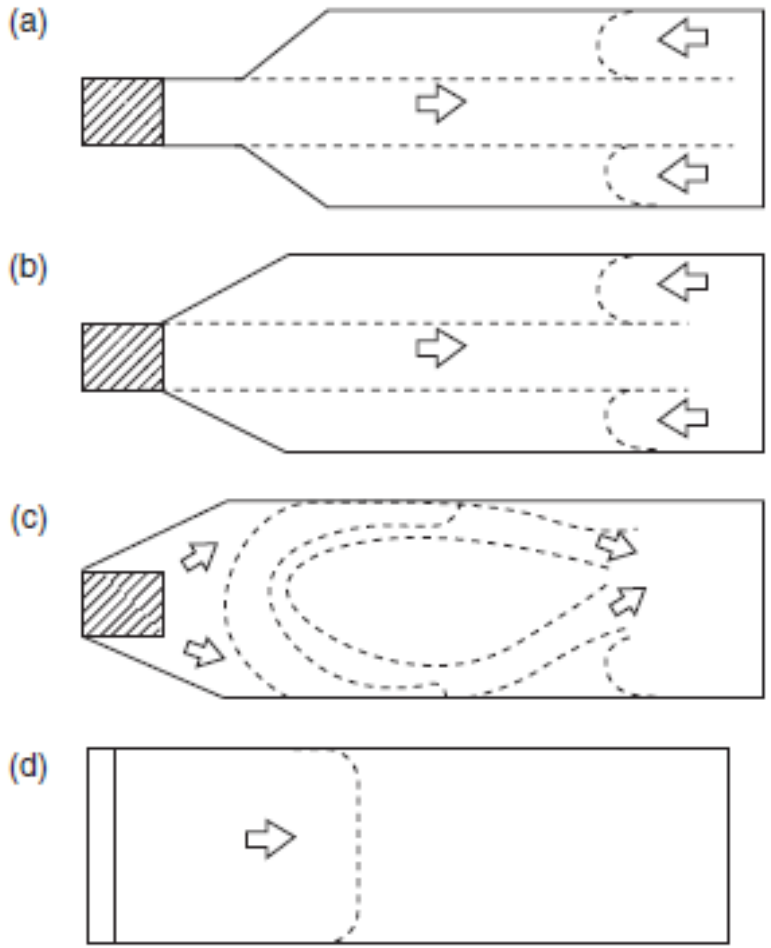
# Base do canal de descida

**Ruim**

**Ruim**

**Ruim**

**Bom**




# Canais de distribuição

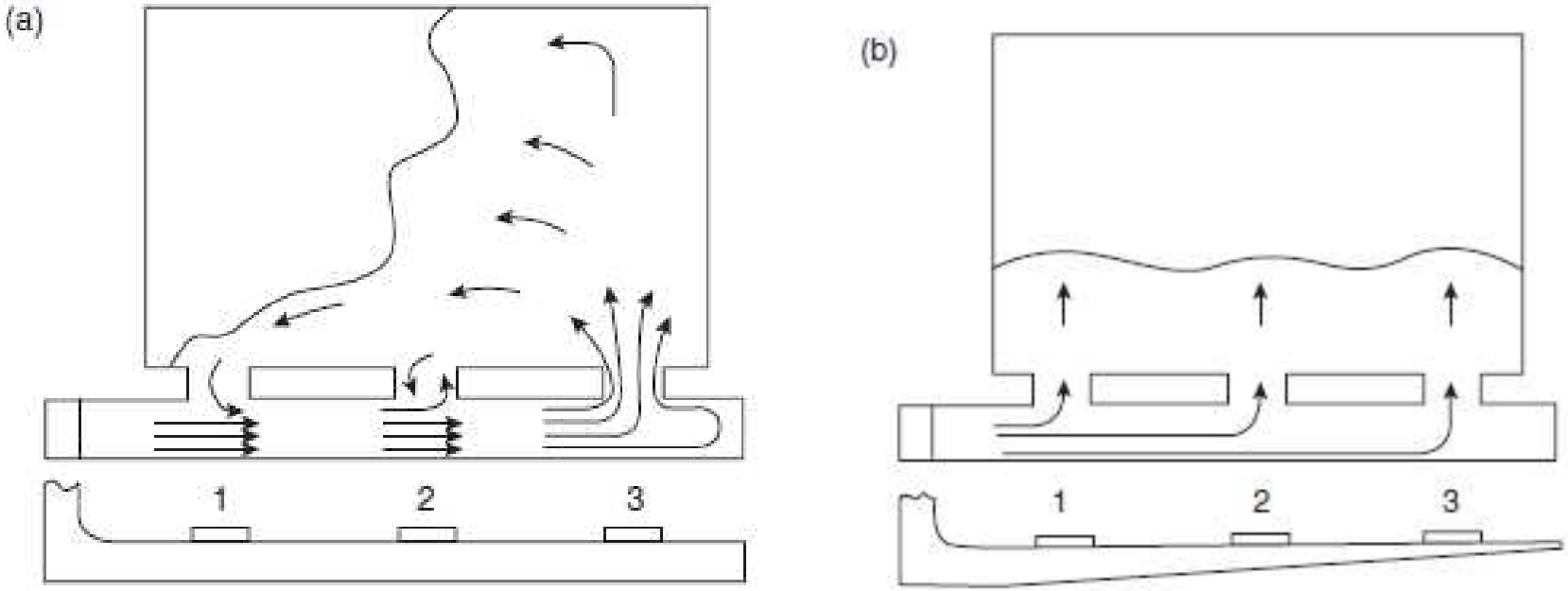



**Figure 2.26** *(a) An unbalanced delivery of melt into the mould as a result of an incorrect runner design; (b) a tolerably balanced system.*

# Uso de filtros

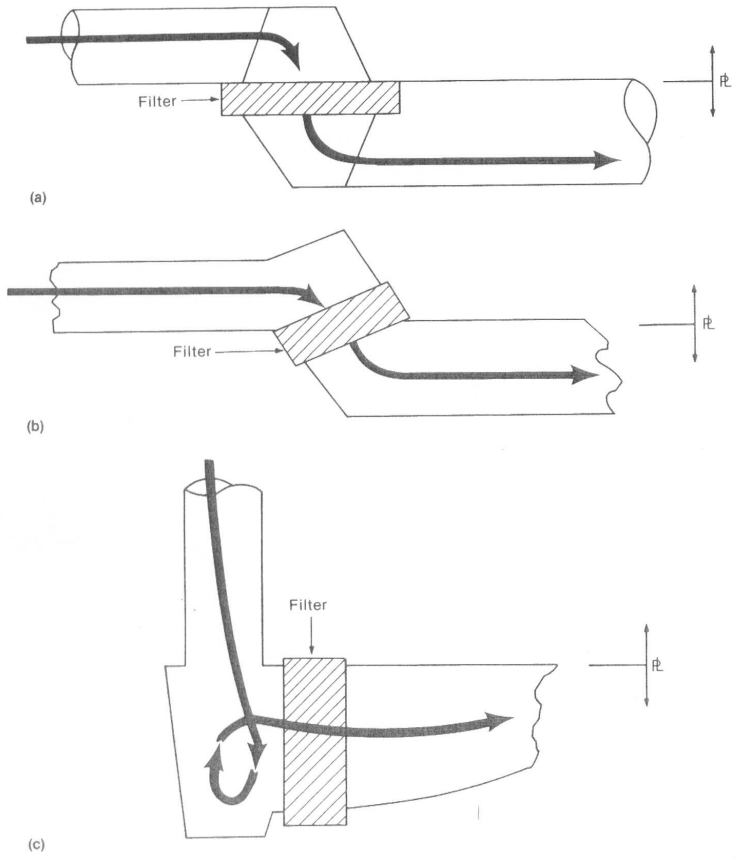



**Fig. 16** Common methods of filter placement in horizontally parted molds. (a) Parallel to parting line. (b) Between 0 and 90° to parting line. (c) 90° to parting line. Arrows indicate the direction of metal flow.

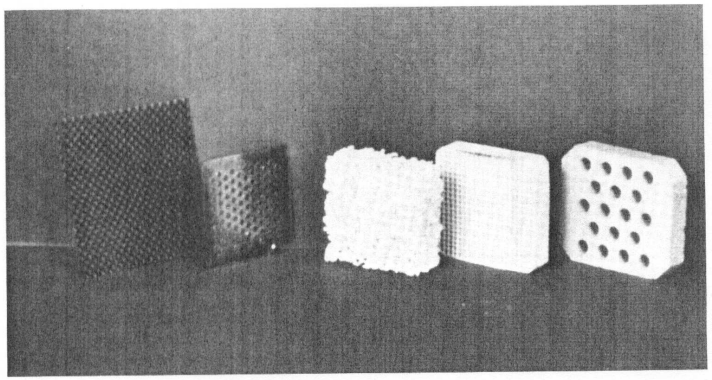


**Fig. 14** Several common filtration and flow modification devices (from left to right): strainer core, extruded ceramic filter, ceramic foam filter, mica screen, and woven fabric screen. The two types of ceramic filters are by far the most widely used.

# Canais de ataque

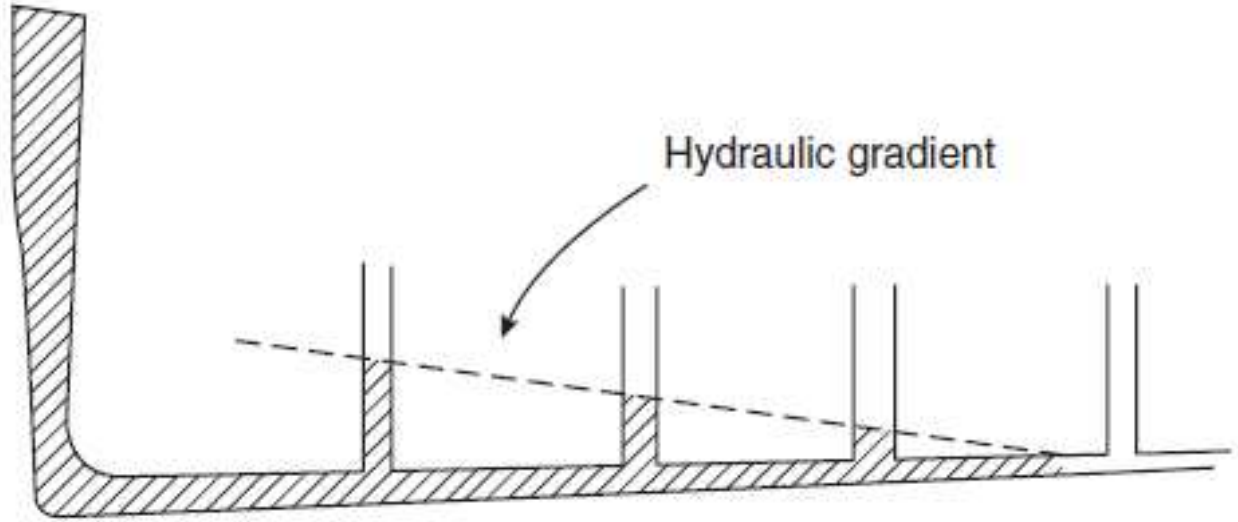



**Figure 2.29** *The partial filling of vertical ingates along the length of a runner.*

# Canais de ataque

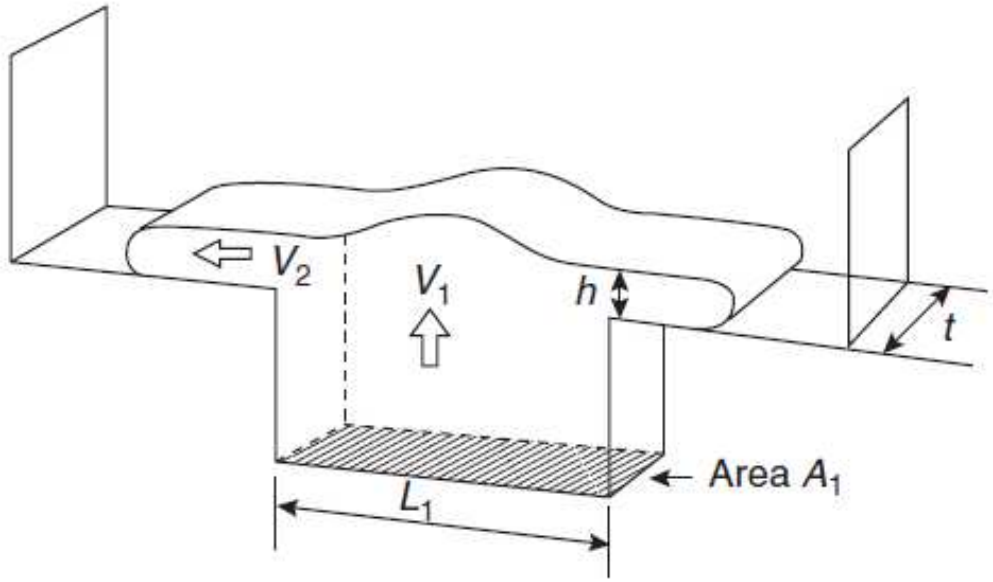



**Figure 2.30** *Sideways flow inside mould cavity.*

$L_1 \leq 2h$

p/ Al h = 13 mm
p/ ferrosos
h = 10 mm

Quando $L_1$ precisa ser maior então usar vários:

$N \geq L_1/2h$

# Canais de ataque

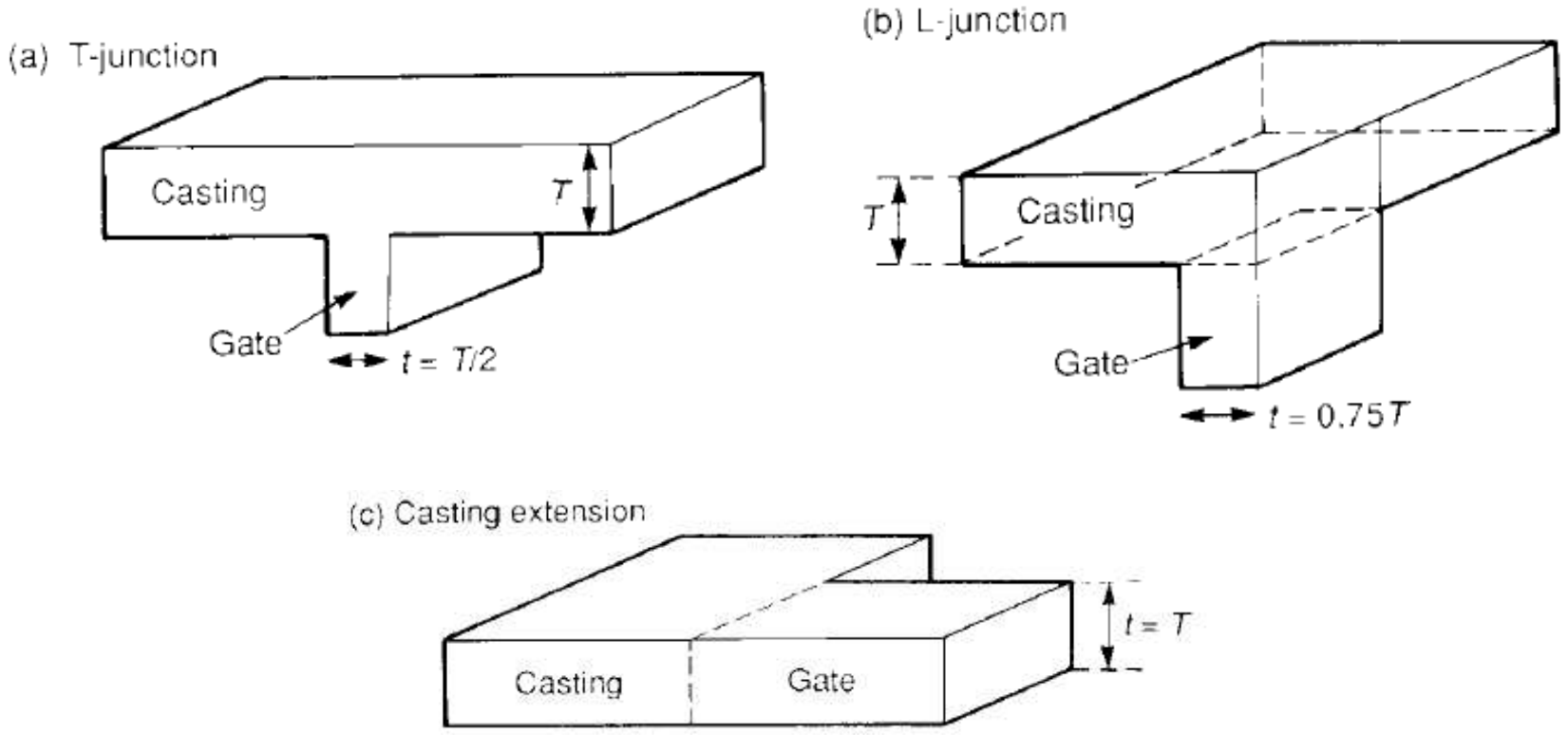
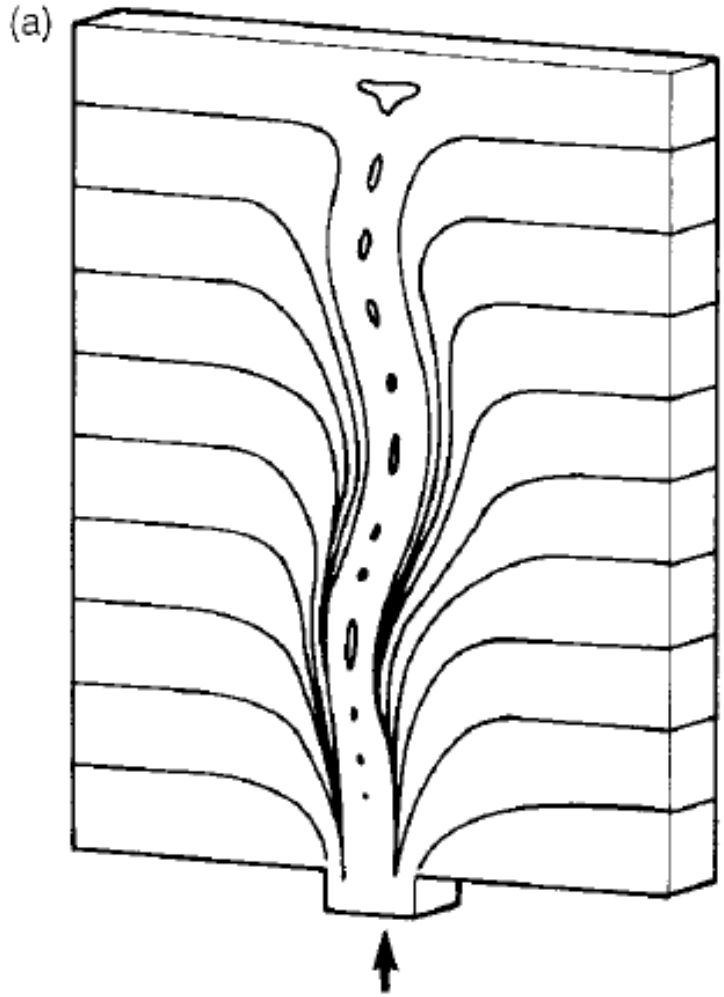



**Figure 2.31** *Maximum allowable gate thickness to avoid a hot spot at the junction with the casting.*

# Efeito do canal de ataque em placas



# Alimentação indireta para placas

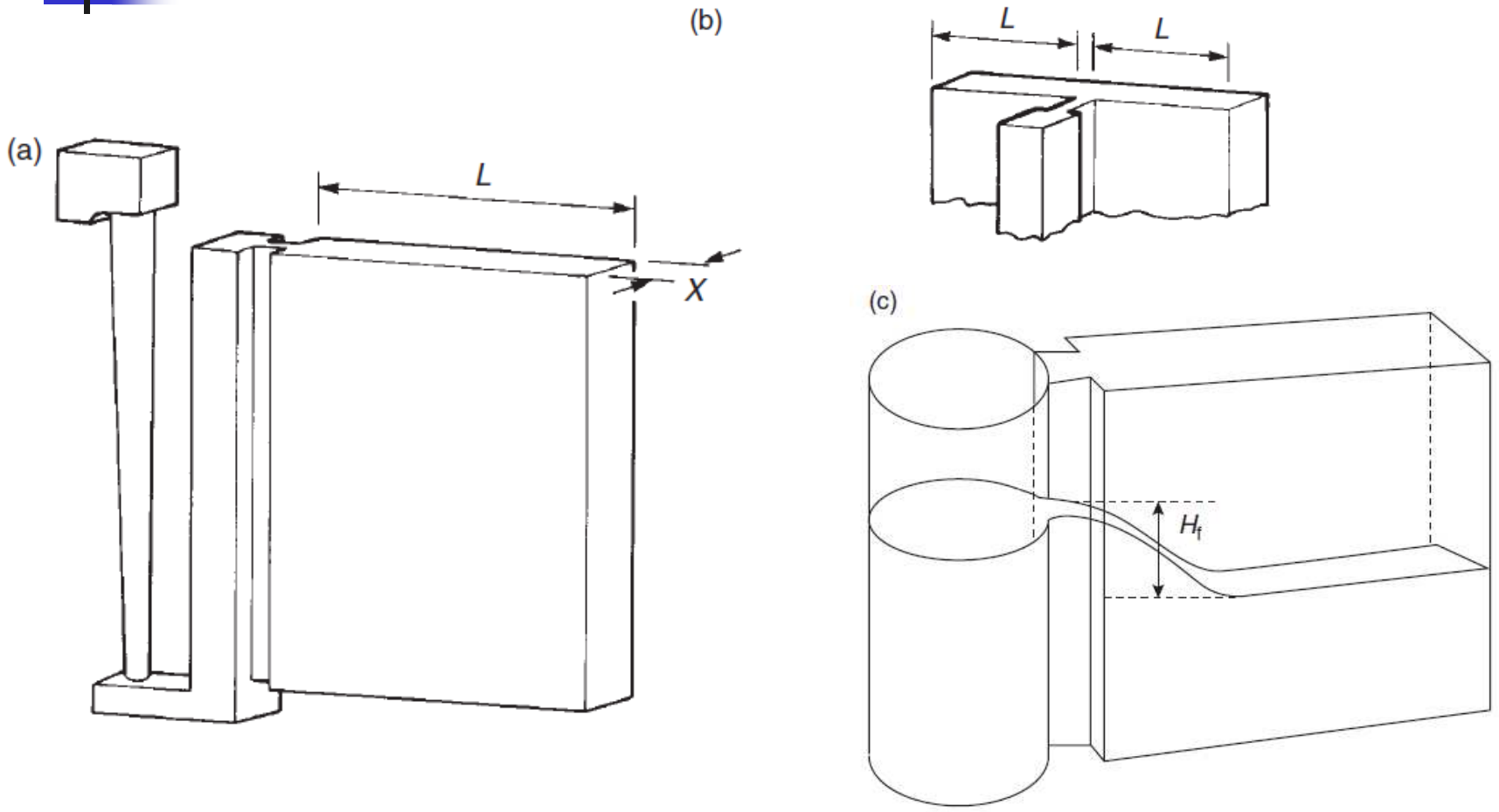



**Figure 2.39** *Riser and slot gate to both gate and feed a vertical plate from (a) its side, or (b) its centre.*

# Efeito de sopro do macho

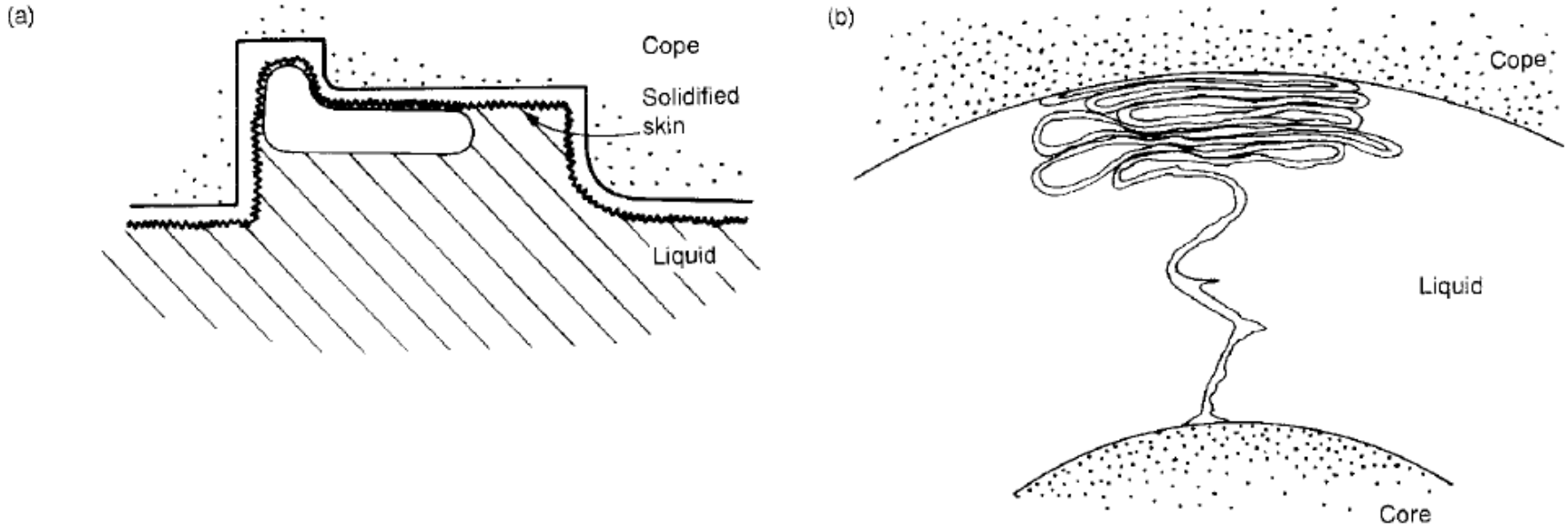
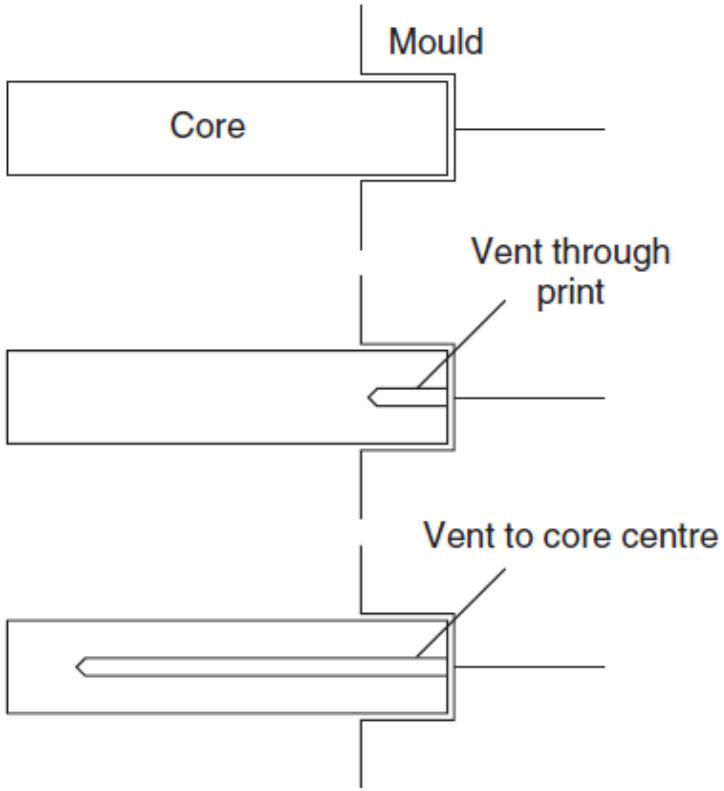



**Figure 5.1** *(a) A core blow—a trapped bubble containing core gases evolved after some solidification; (b) an exfoliated dross defect produced by copious gas from a core blow prior to any solidification.*

# Prevenindo o sopro do macho



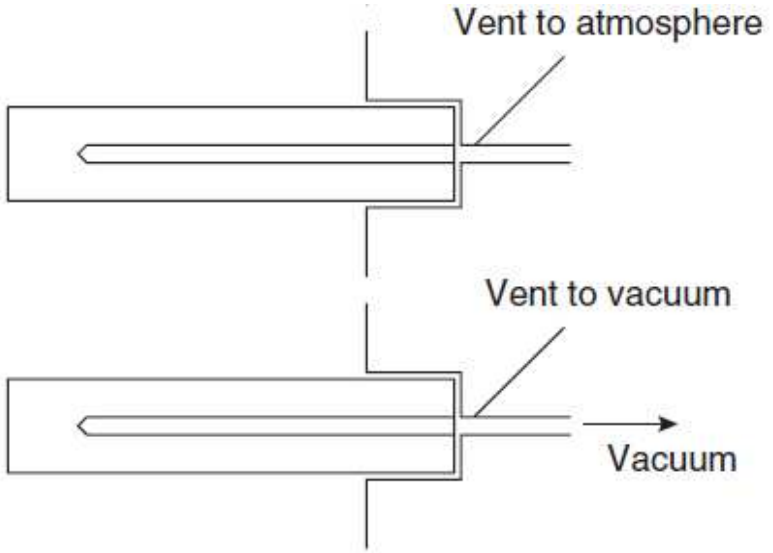
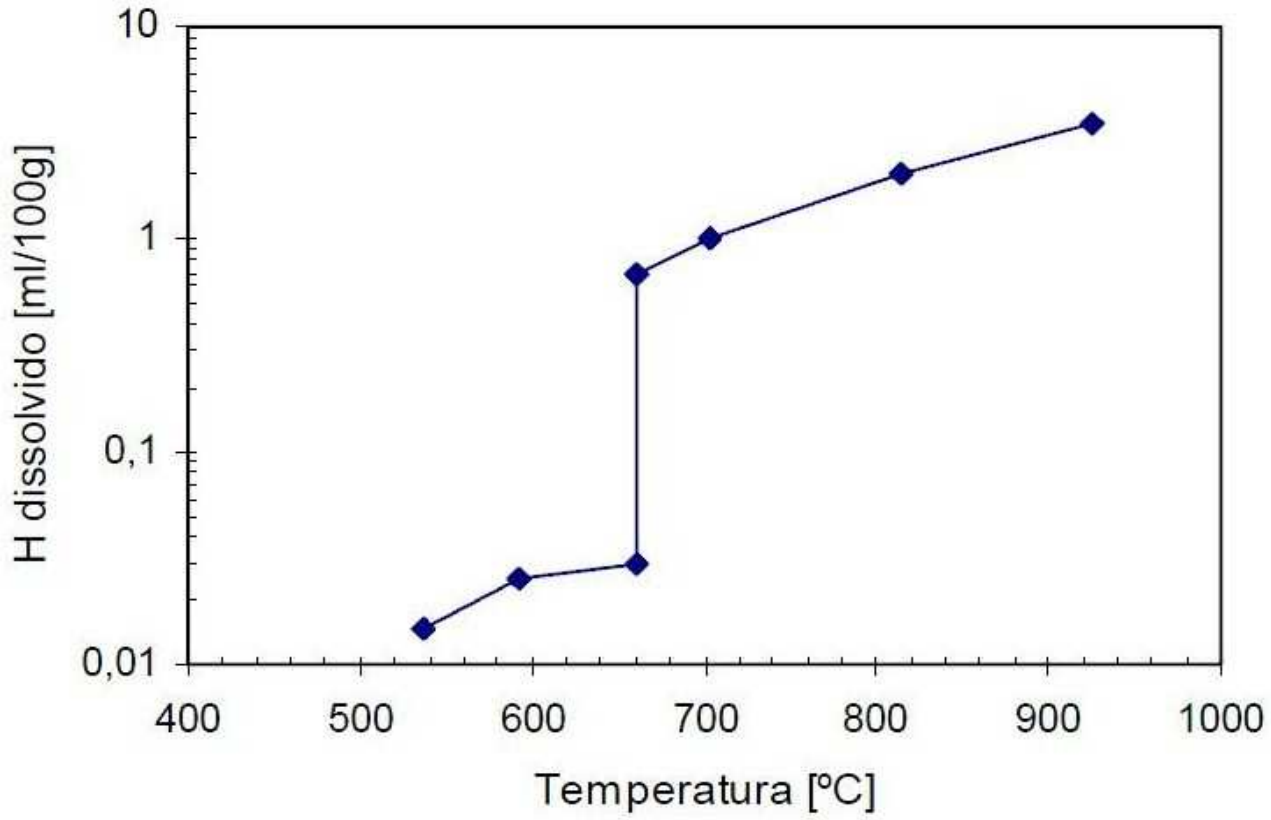




**Figure 5.4** *Venting of a core, illustrating progressively improved techniques.*

# Importante:
# Metal líquido de qualidade

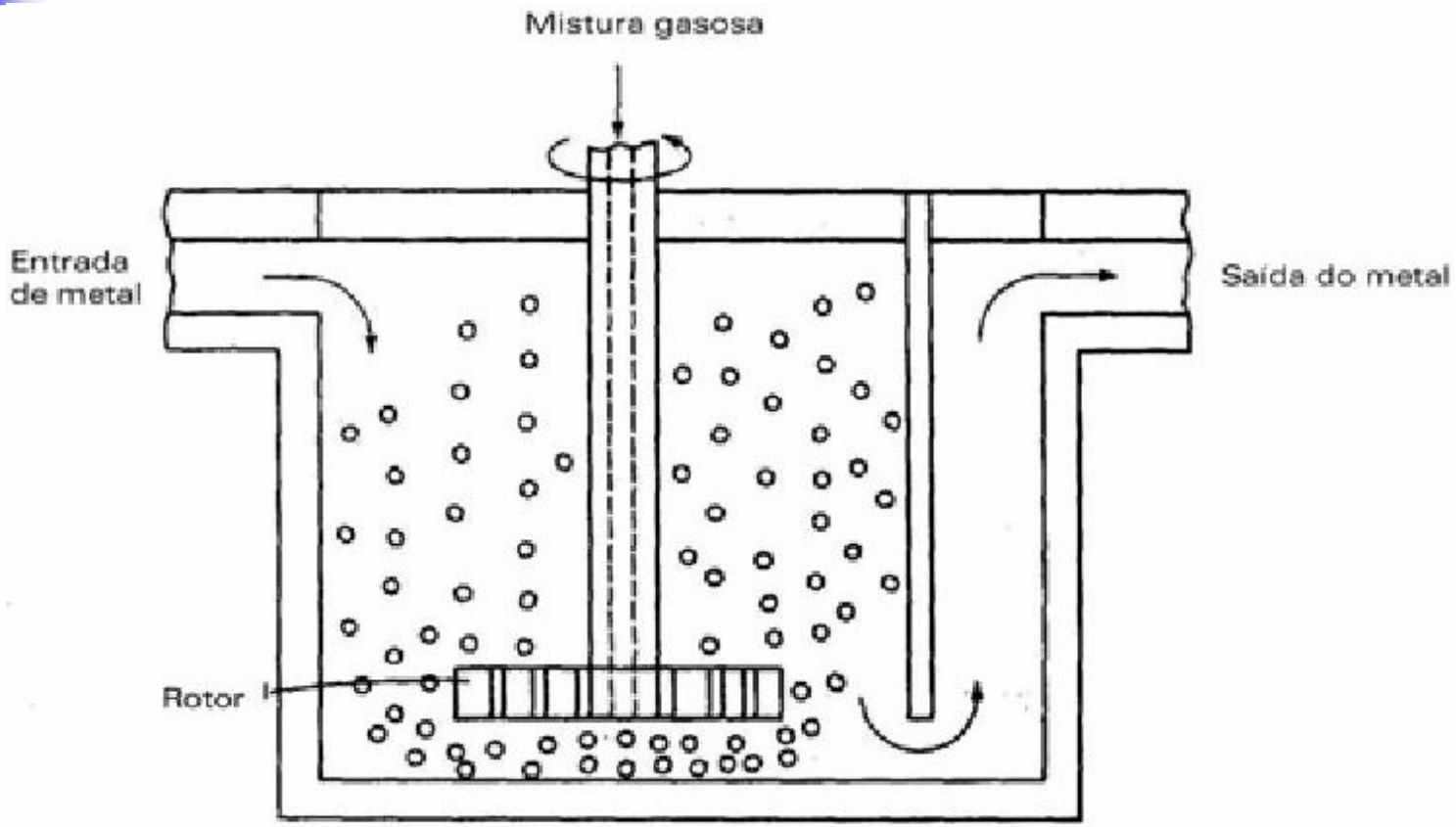
- Livre de gases
- Livre de inclusões de escória
- Na composição química correta

# Exemplo: desgaseificação de Al



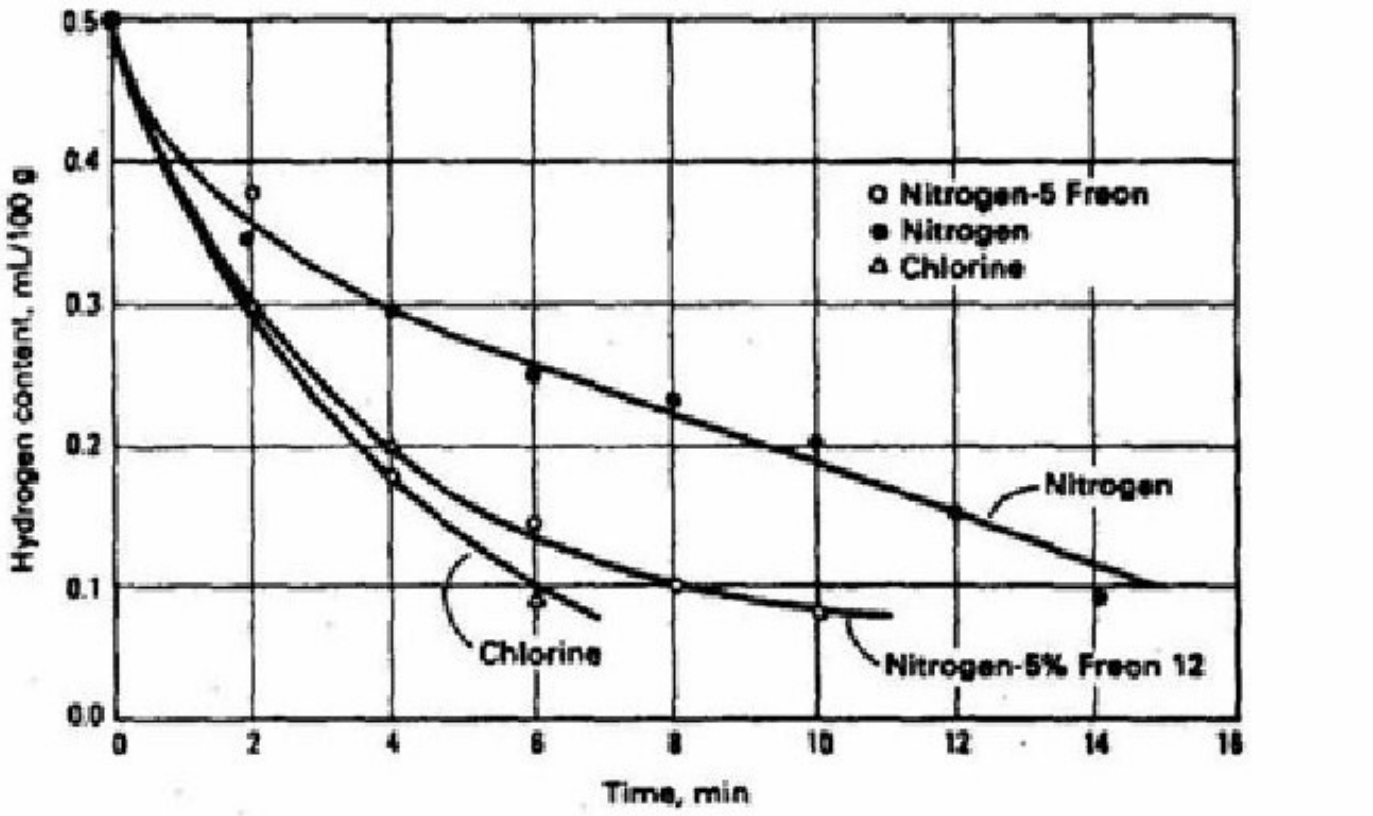

Solubilidade do H no Al

# Exemplo: desgaseificação de Al




Esquema de uma unidade de desgaseificação contínua (rotor).

# Exemplo: desgaseificação de Al




Redução do teor de H dissolvido no banho com o tempo de desgaseificação.

# Bibliografia das Aulas


- GARCIA, Amauri, Solidificação – fundamentos e aplicações, UNICAMP, 2a ed., 2007
- CAMPOS FILHO, Mauricio Prates de e DAVIES, Graeme John. Solidificação e fundição de metais e suas ligas, Rio de Janeiro: Livros Técnicos e Científicos, 1978.
- American Society for Metals. ASM Handbook Committee. Metals Handbook (Casting), 9a ed., vol. 15, Ohio, 1988.
- KALPAKJIAN, Serope e SCHMID, Steven. Manufacturing processes for engineering materials, 5a ed., Pearson Education, New Jersey, 2007.
- CAMPBELL, John, Castings, Elsevier, Oxford, 2ª ed., 2004.
- CAMPBELL, John, Castings practice – the 10 rules of castings, Elsevier, Oxford, 2004.