



PME 3430

Materiais para Construção Mecânica

Profs. Drs.: Newton K. Fukumasu, Deniol K. Tanaka & Amilton Sinatora

Referências:

CALLISTER, William D., *Materials science and engineering: an introduction*. 8ed. New York: John Wiley, 2009. 122p. ISBN-13: 978-0-471-73696-7

MEYERS, M. A. & Chawla K. K. *Mechanical Behavior of Materials*. Prentice Hall, 1999, 680. ISBN 0-13-262817-1 2



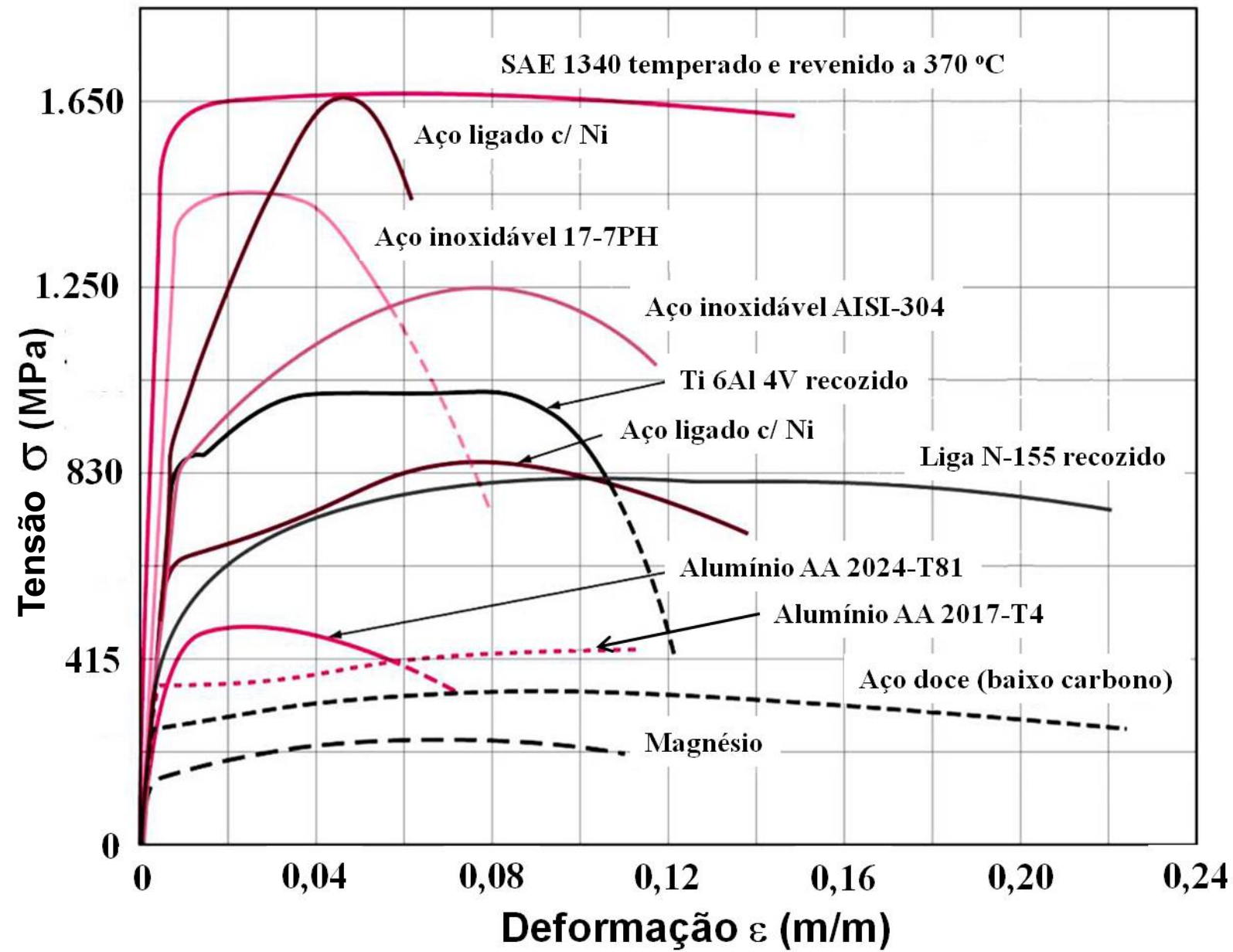
Cronograma de Atividades – 1º Semestre 2017

Proposta – 2

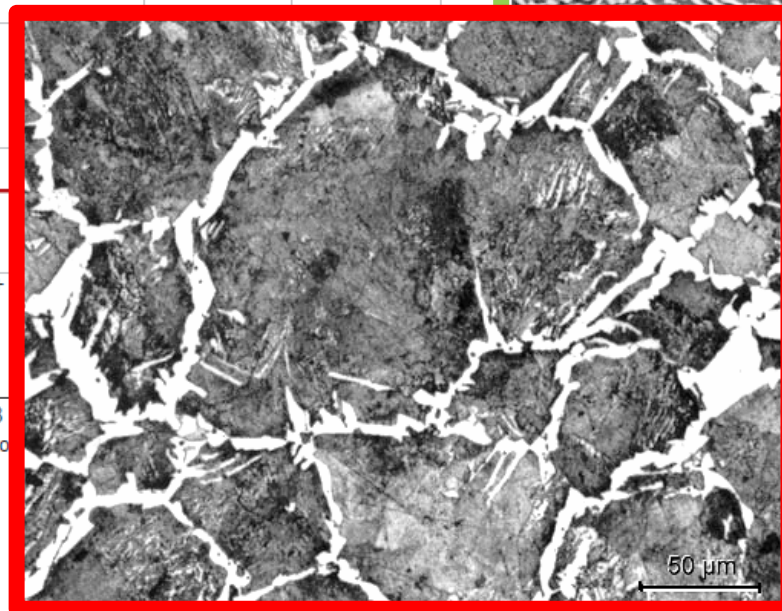
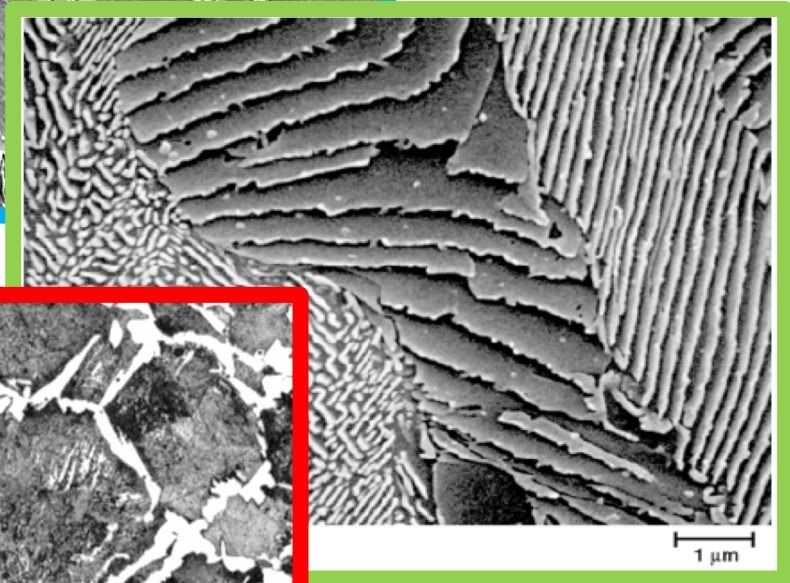
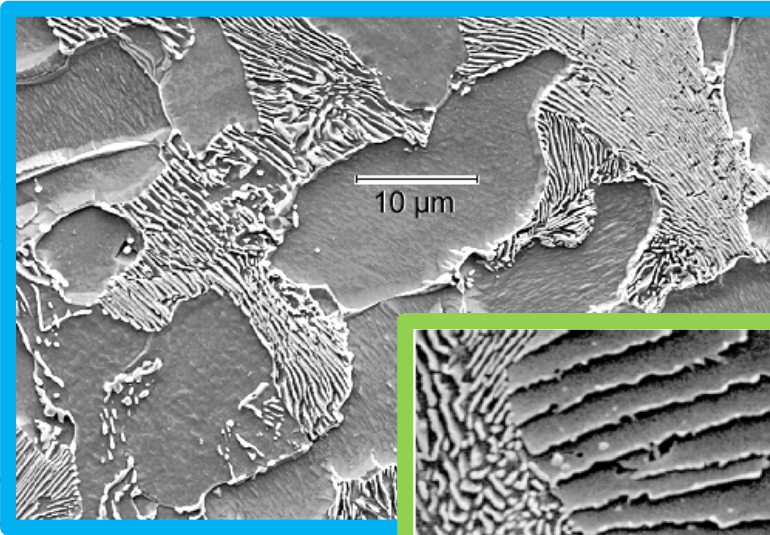
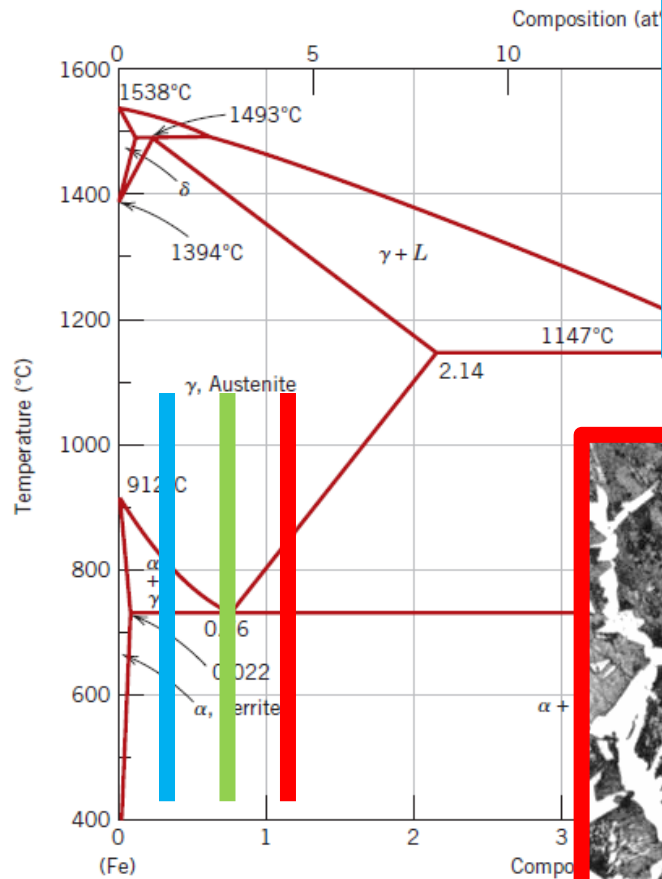
Aula	Data	Tópico do Programa
01	08/03	Apresentação da disciplina, critérios de avaliação e revisão de conceitos
02	15/03	Definição dos temas de trabalho e revisão de conceitos
03	22/03	Processamento de ligas metálicas (fundição)
04	29/03	Processamento de ligas metálicas (laminação e forjamento)
05	05/04	Tratamento térmico de ligas metálicas (diagrama TTT)
-	12/04	SEMANA SANTA – Não haverá aula
06	19/04	Tratamento de superfícies de ligas metálicas (químico e mecânico)
07	26/04	Processamento de polímeros (polimerização, borrachas e vulcanização)
08	03/05	Polímeros avançados (vítreos, piezos)
09	10/05	PROVA – P1 e entrega de TRABALHOS – T1
10	17/05	Processamento de cerâmicas (fundição e sinterização)
11	24/05	Processamento de cerâmicas (tratamento térmico)
12	31/05	Cerâmicas avançadas (piezos e termo-elétricos)
13	07/06	Recobrimentos cerâmicos (carbonetos, nitretos, óxidos)
14	14/06	Compósitos metal/cerâmicos (ferramentaria)
15	21/06	Compósitos polímero/cerâmicos (fibras de carbono, aramida)
16	28/06	Entrega de TRABALHOS – T2
17	05/07	PROVA – P2
18	07/07	PROVA Substitutiva



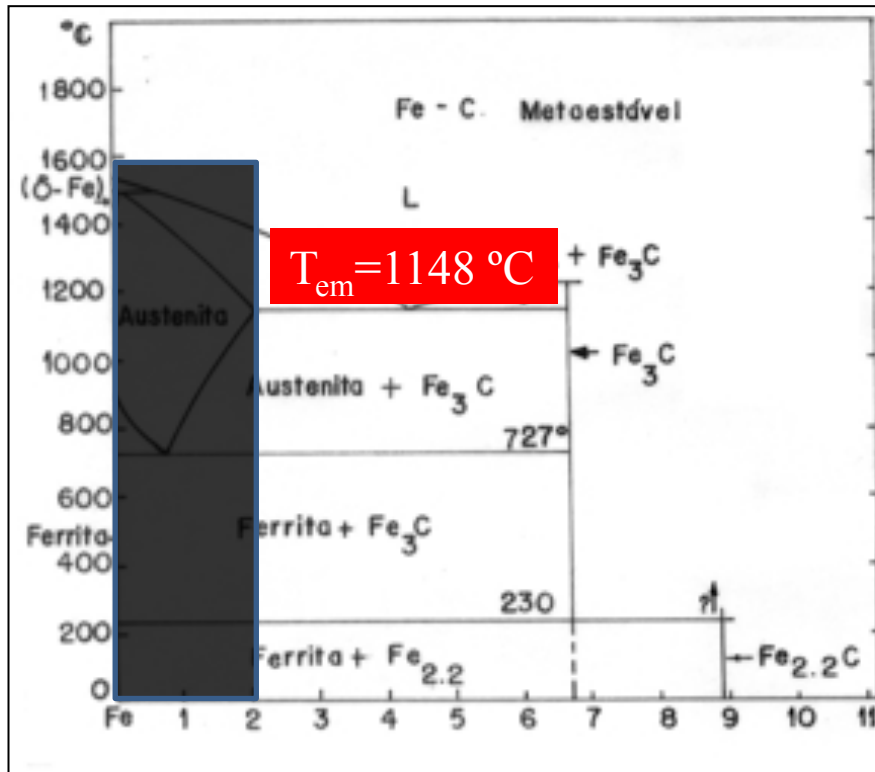
Curva tensão X deformação de metais



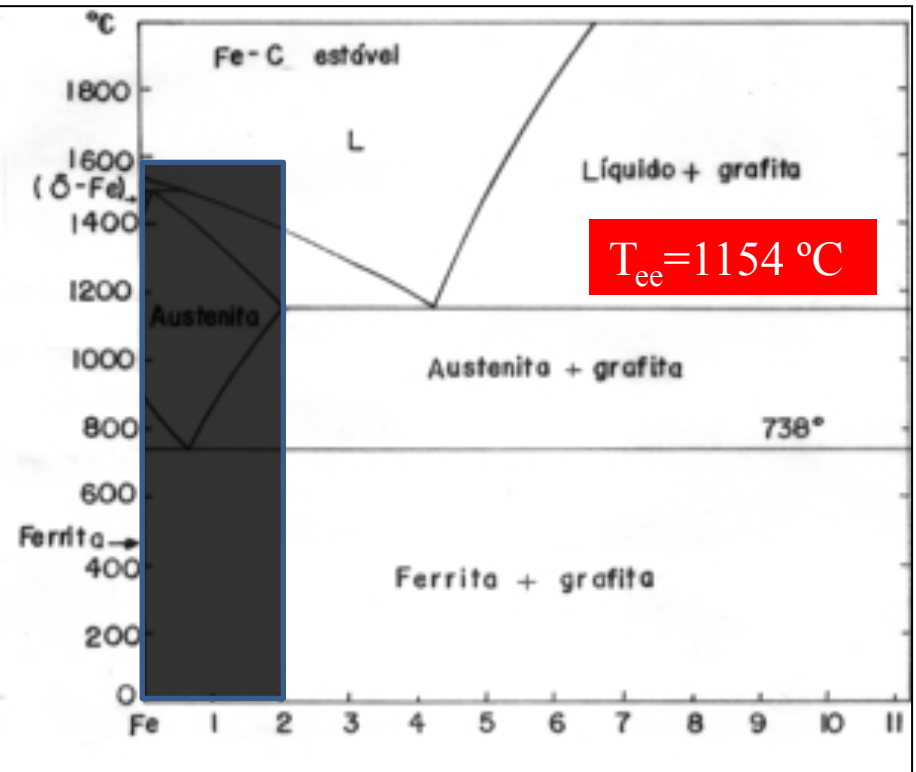
Sistema Ferro X Carbono – Aços



Sistema Ferro X Carbono – Ferro Fundido



Formação de Cementita (Fe_3C)

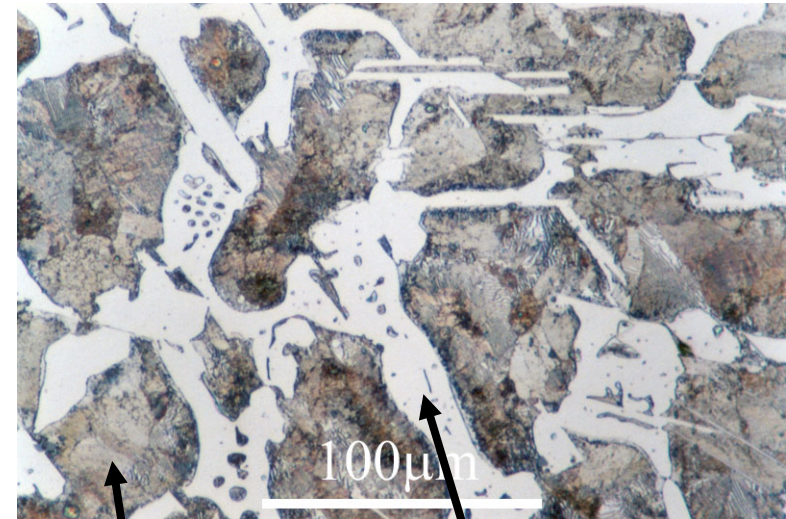


Formação de Grafita (C)

Ferro Fundido – Carboneto

Carbonetos M_3C

Ferro fundido branco

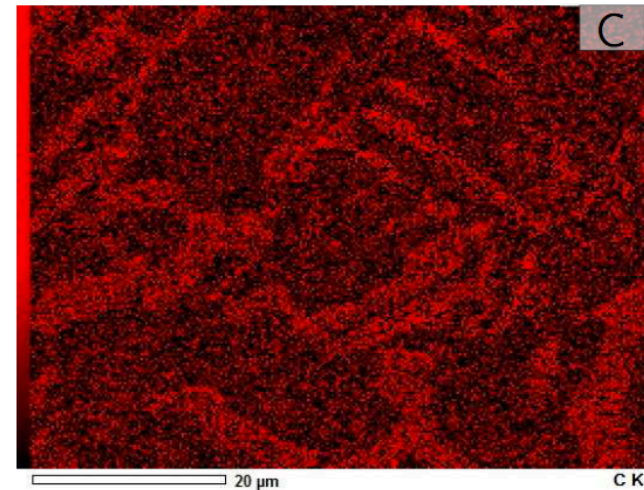
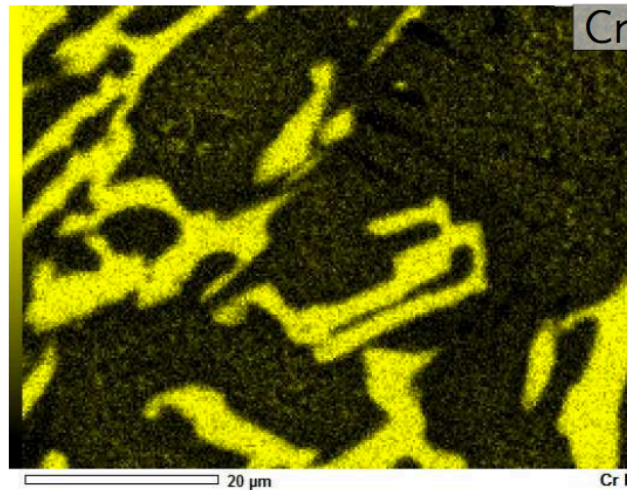
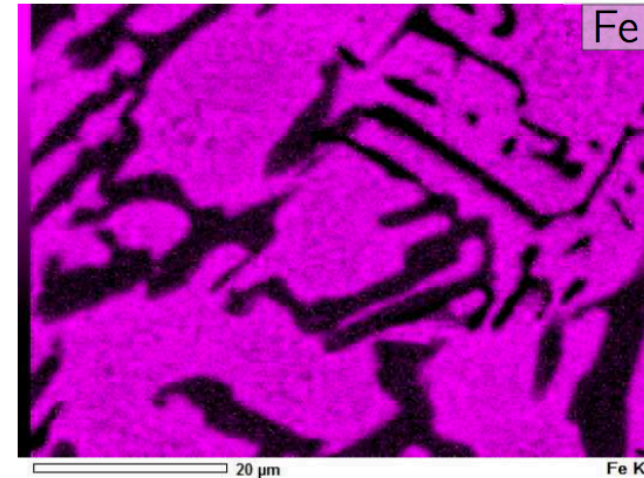
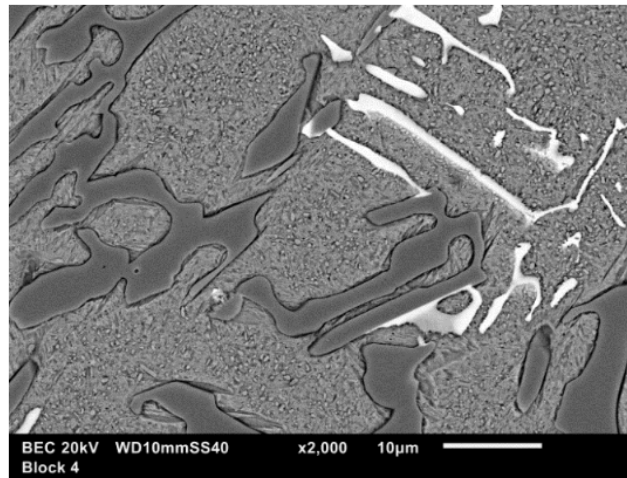


Perlita

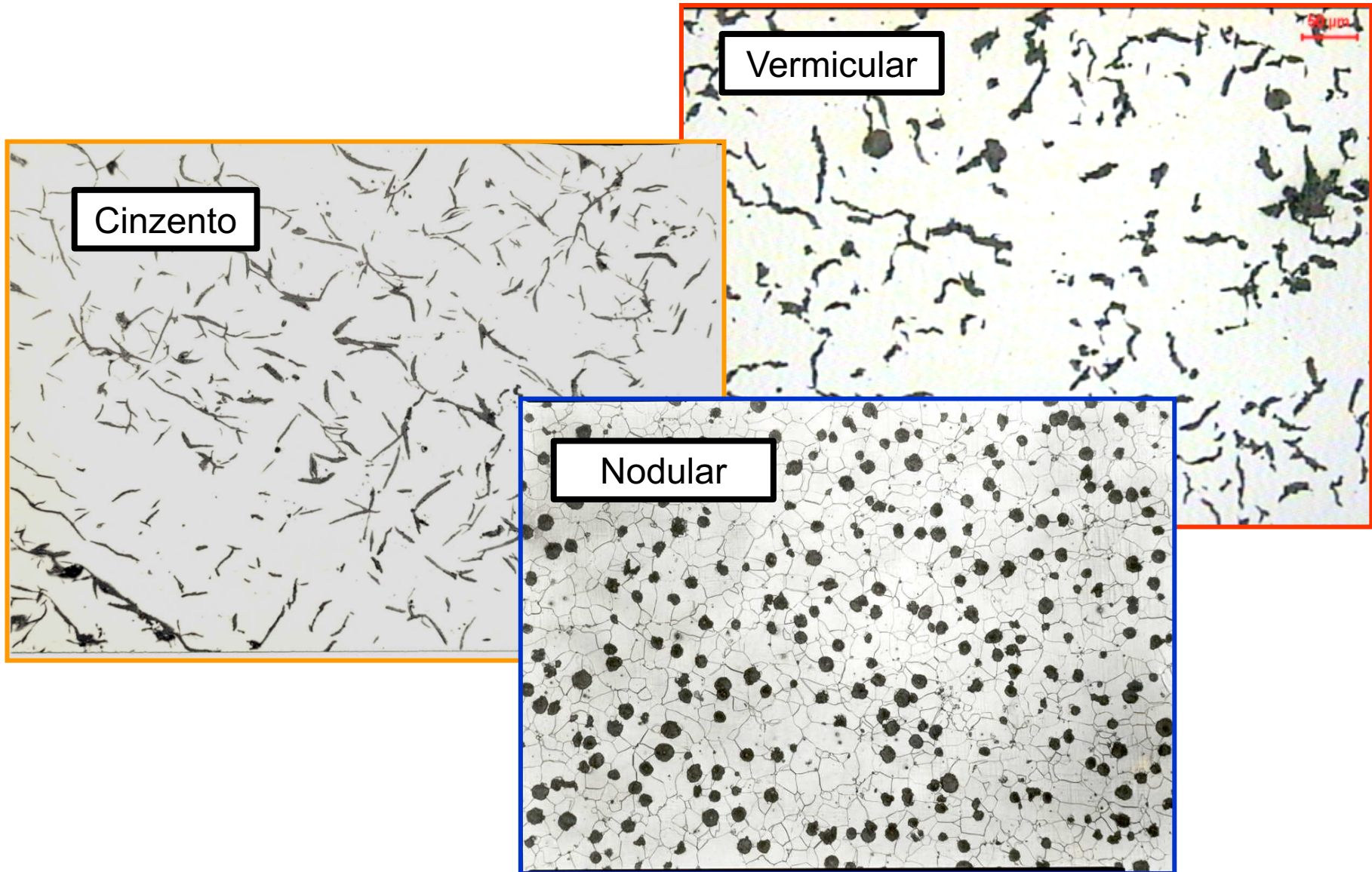
Cementita + Ferrita

Ferro Fundido – Carboneto

Carbonetos M_7C_3 - *Ferro fundido branco alto cromo*

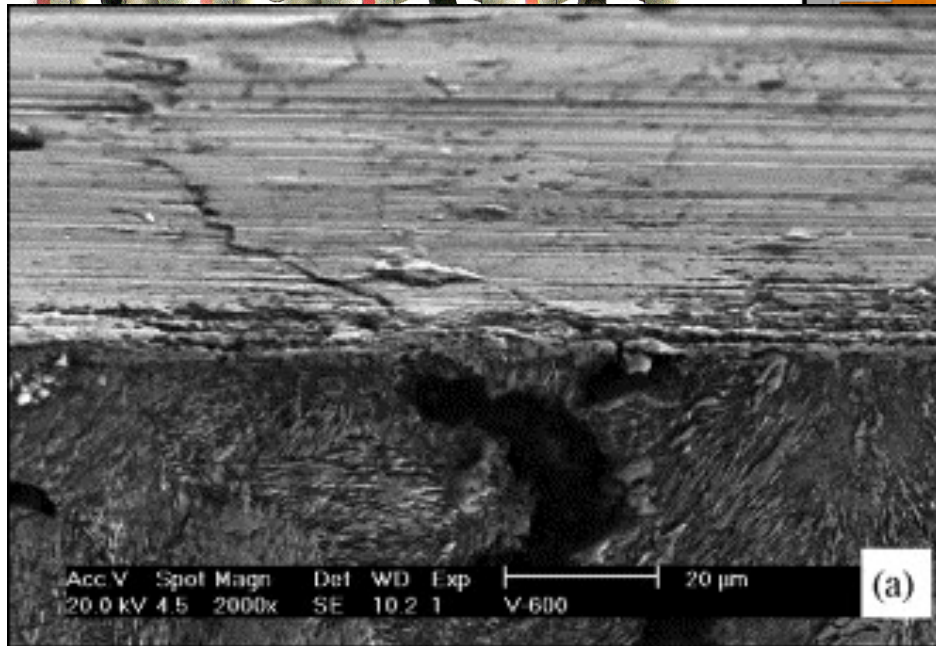
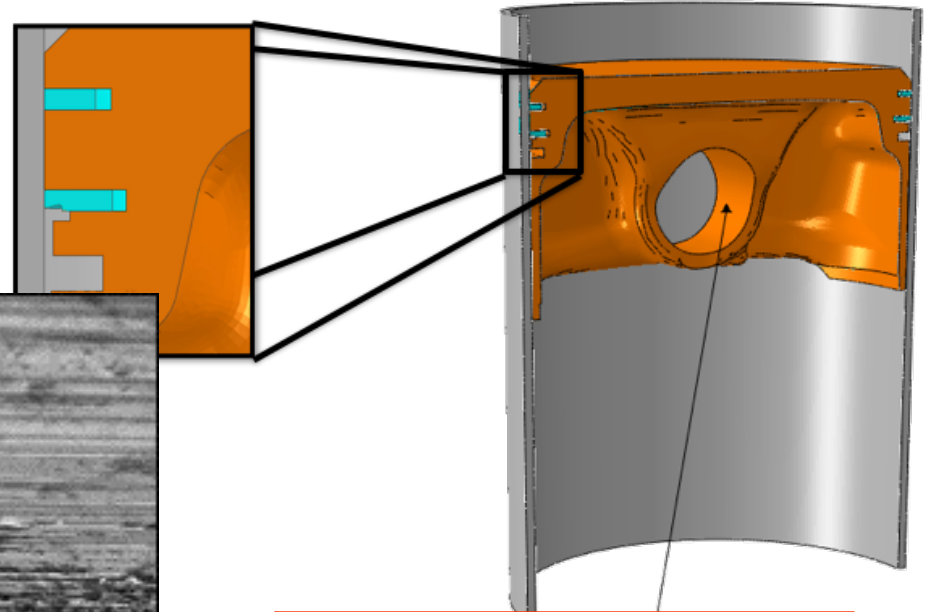
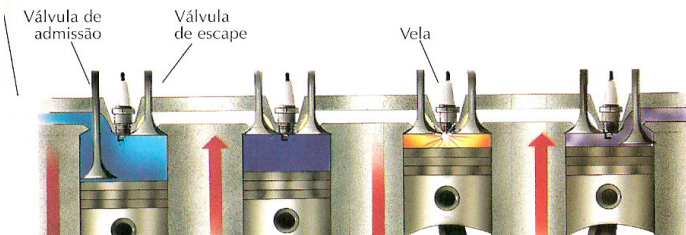


Ferro Fundido – Grafita



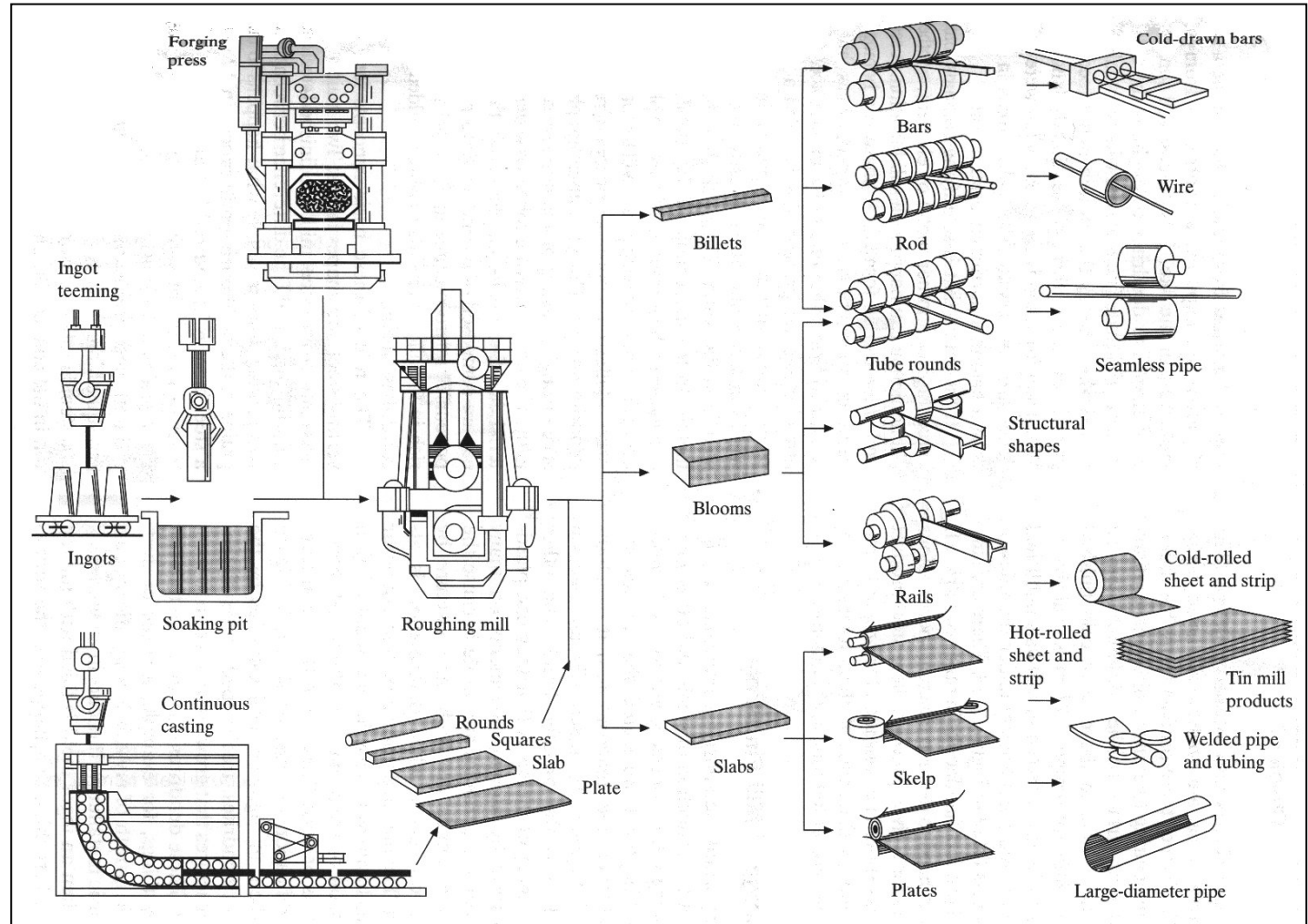
Ferro Fundido – Grafita

❖ Aplicação na camisa do motor

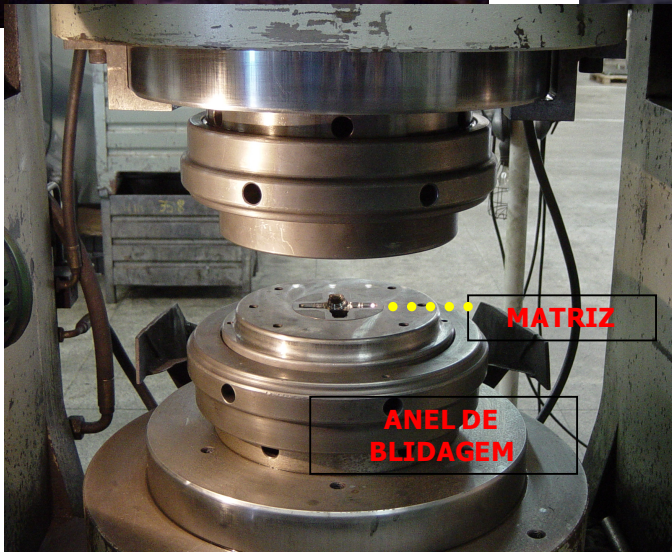


Processos siderúrgicos

- ❖ Fundição
- ❖ Laminação
- ❖ Forjamento



Processo Siderúrgicos



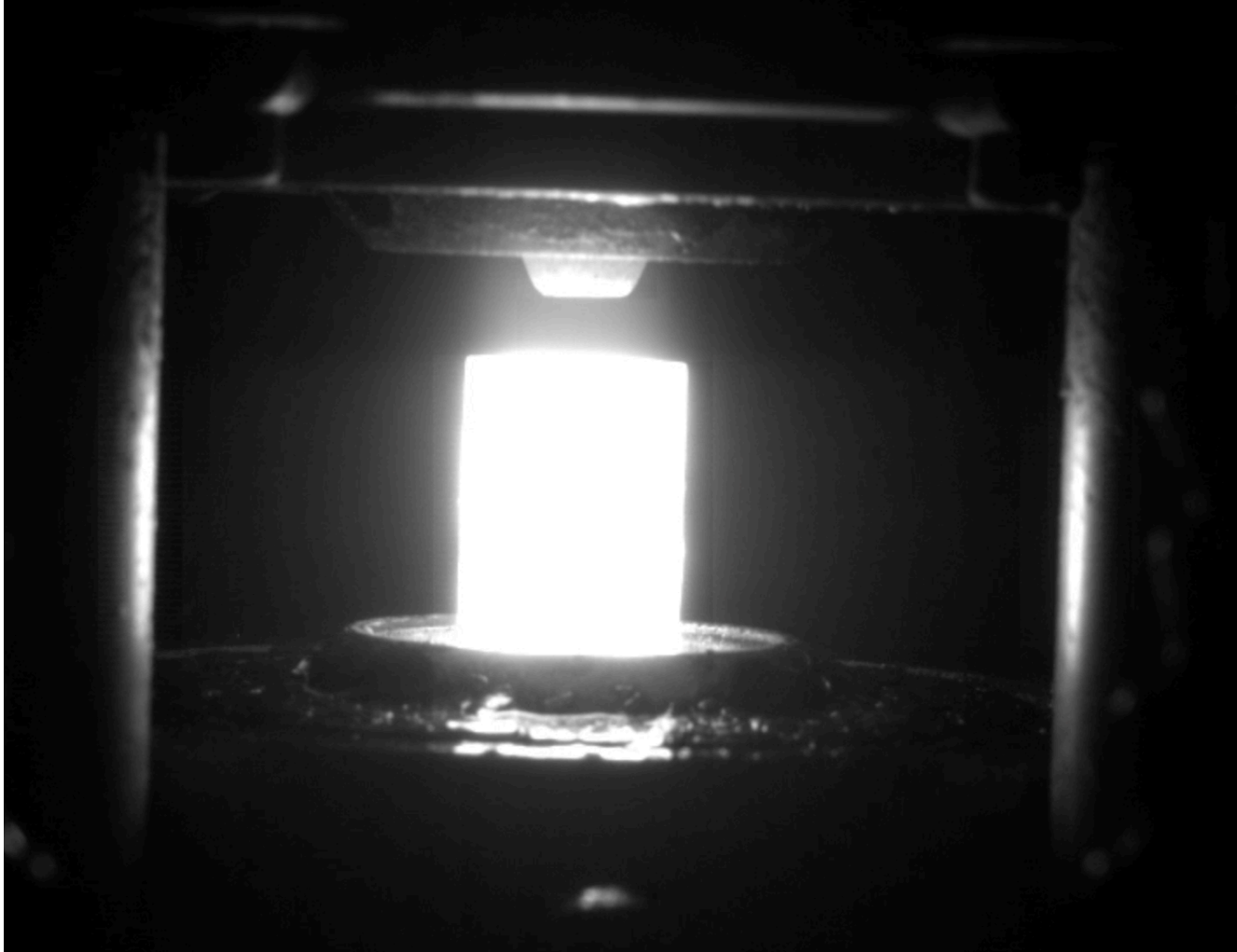


Laminação

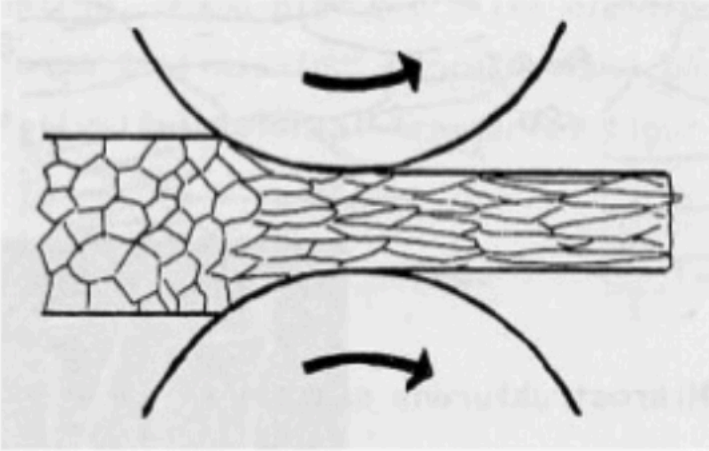
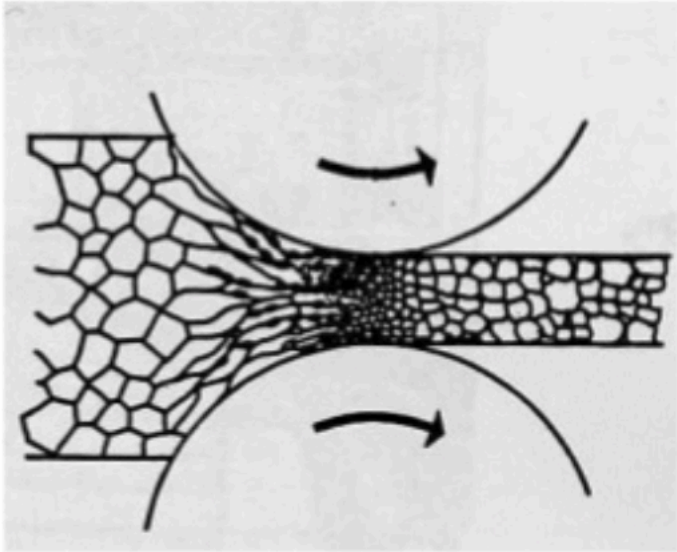




Forjamento



Laminação

Cold Rolling	Hot Rolling
 The diagram illustrates the cold rolling process. A metal strip with a coarse, irregular grain structure enters from the left and passes between two curved rollers. The rollers rotate in opposite directions, indicated by curved arrows. As the strip exits to the right, its grain structure is significantly refined and elongated in the direction of rolling, indicating a higher degree of deformation.	 The diagram illustrates the hot rolling process. A metal strip with a coarse, irregular grain structure enters from the left and passes between two curved rollers. The rollers rotate in opposite directions, indicated by curved arrows. As the strip exits to the right, its grain structure is refined and elongated, but it appears less refined than in the cold rolling process, reflecting the higher temperature and lower deformation resistance.

<https://www.slideshare.net/palanivendhan/mechanical-working-of-metals-37308919>



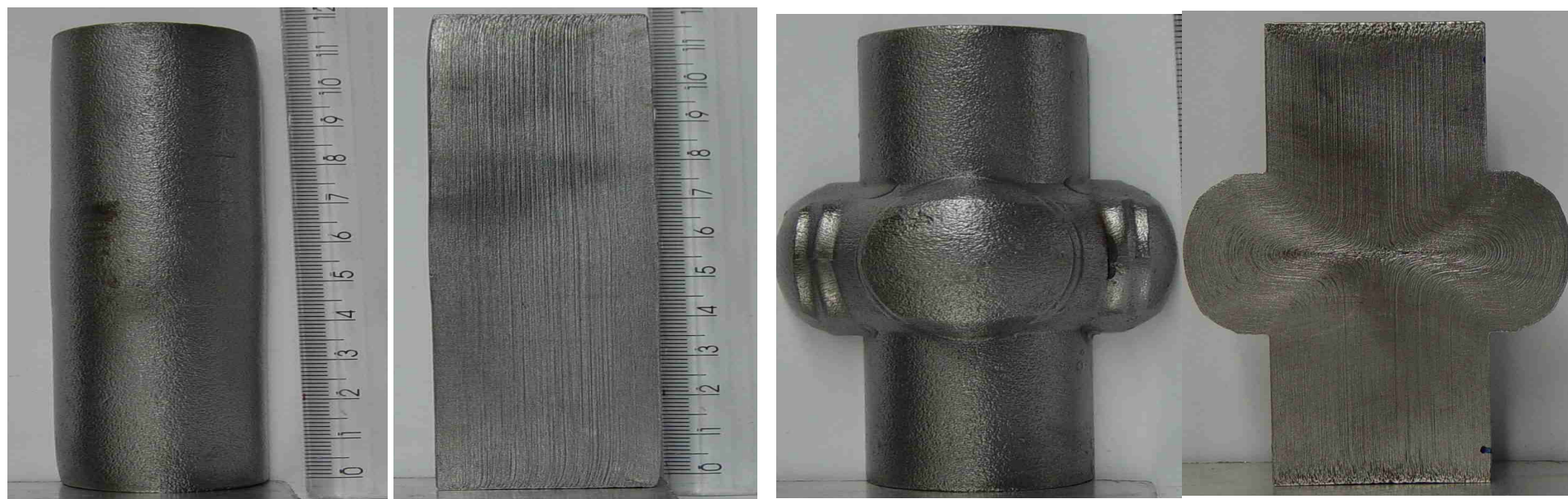
Forjamento

Inicial

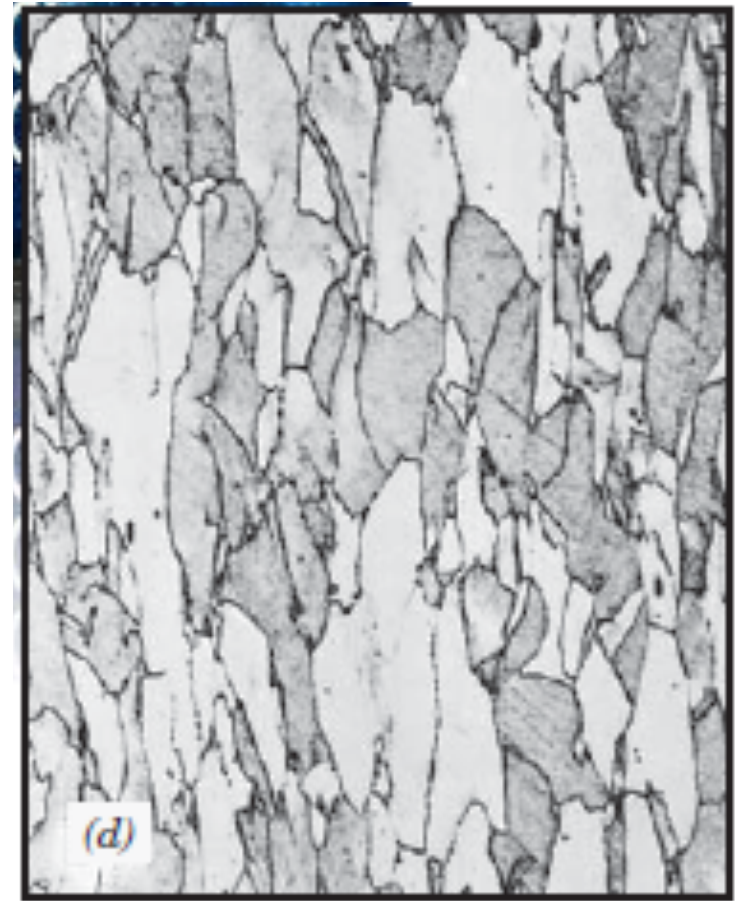
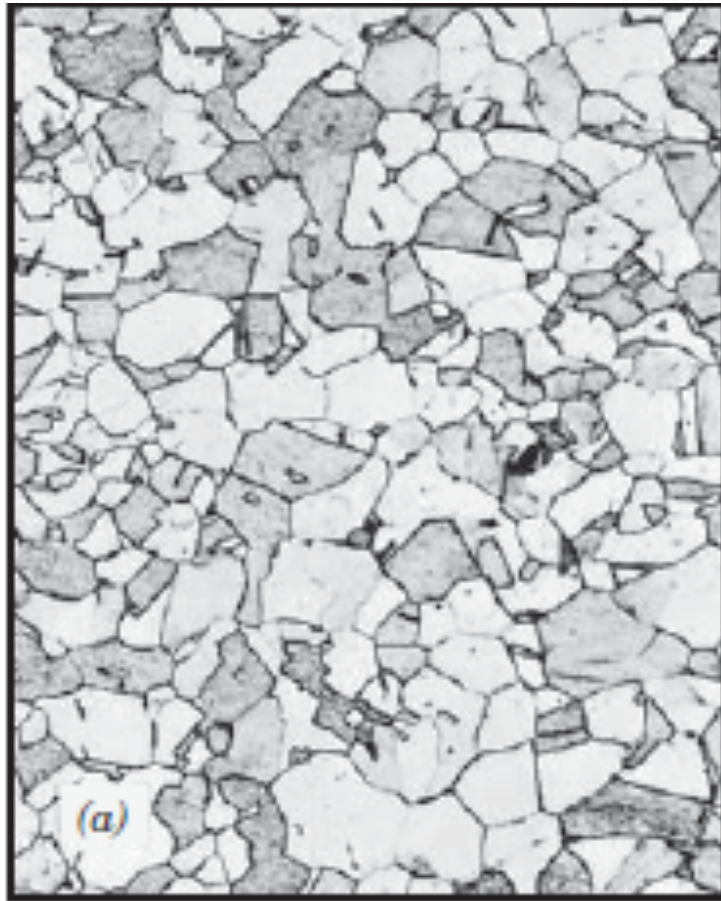
Altura = 79,12 mm

Redução percentual da altura = 33,85 %

Relação deformação (h/d) = 2,62

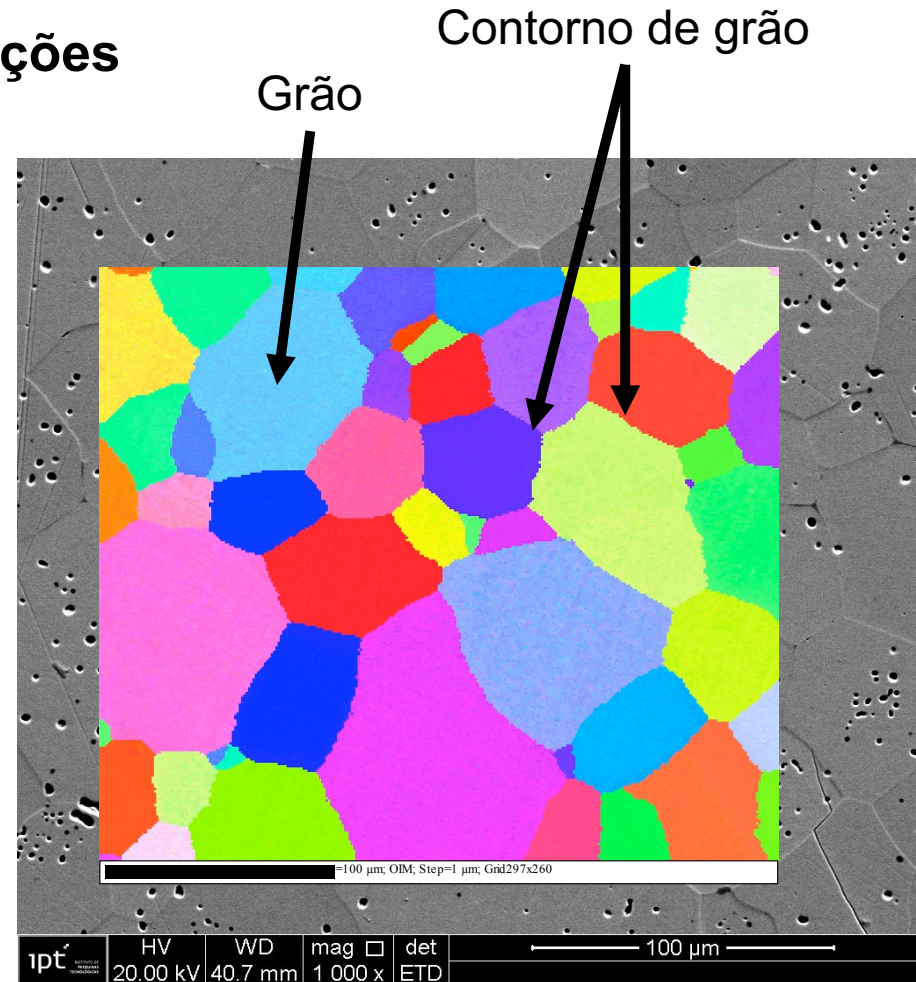
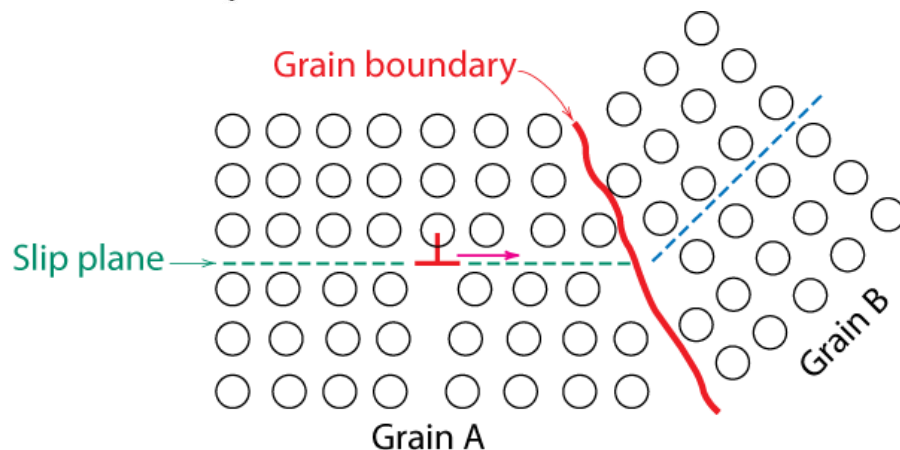
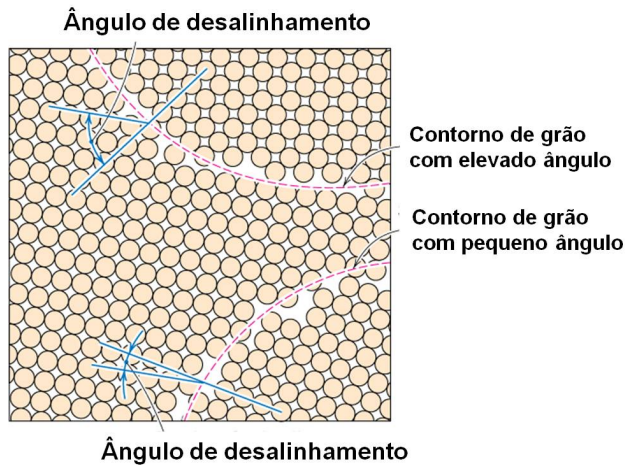
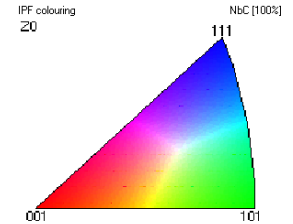


Laminação e Forjamento



Influência do contorno de grão

- ❖ Material policristalino
- ❖ Carboneto de Nióbio cúbico
- ❖ Grãos com diferentes orientações





Tamanho de grão & resistência mecânica

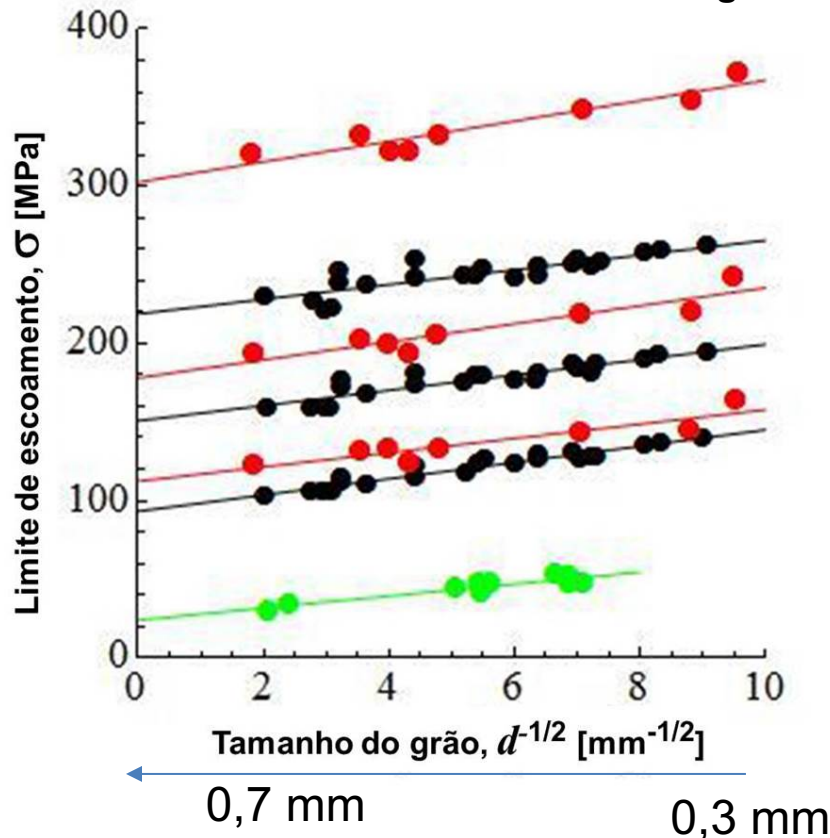
$$\sigma_y = \sigma_0 + k_y d^{-1/2} \quad \text{Hall \& Petch}$$

σ_y = Tensão para a qual o material se deforma plasticamente

σ_0 = Constante do material – valor para início da movimentação de discordâncias

k_y = Constante do material

d = tamanho médio dos grãos



● Cu(1)
 T_{Nliq}

Hansen, N., Ralph, B., 1982. The strain and grain size dependence of the flow stress of copper. Acta Met. 30, 411–417.

● Cu(2)
 T_{amb}

Hansen, N., Ralph, B., 1982. The strain and grain size dependence of the flow stress of copper. Acta Met. 30, 411–417.

● Cu(3)

Armstrong, R.W., Elban, W.L., 2012. Hardness properties across multiscales of applied loads and material structures. Mater. Sci. Technol. 28, 1060–1071.



Laminação e forjamento

❖ **Mudança nas propriedades dos materiais**

❖ **Processos a frio**

- ❖ **Reorientação preferencial dos grãos na direção de escoamento do material**
- ❖ **Aumento de tensão residual compressiva**
- ❖ **Diminuição da ductilidade**
- ❖ **Melhor acabamento superficial**

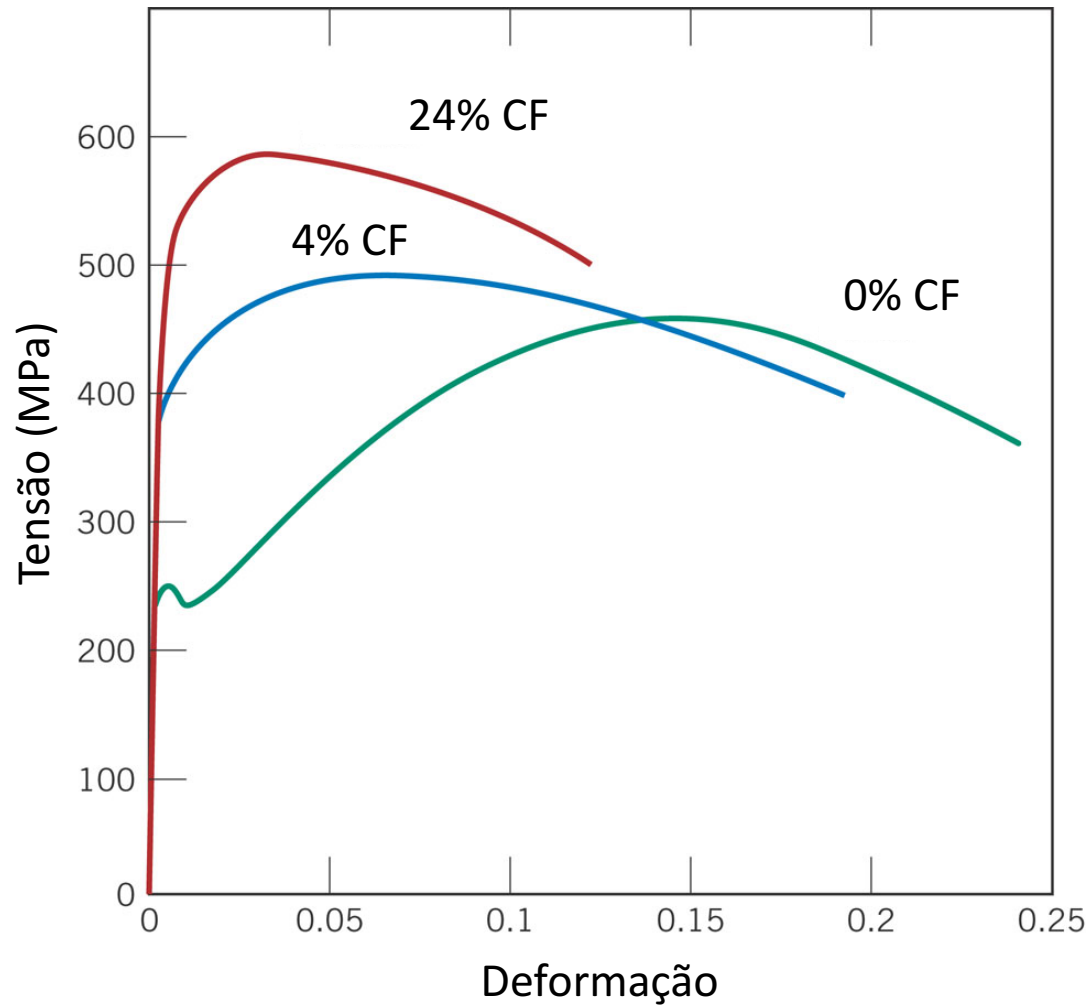
❖ **Processos a quente**

- ❖ **Recristalização dos grãos com diminuição do diâmetro**
- ❖ **Alívio de tensões do processo**
- ❖ **Problemas com acabamento superficial**



Influência do processo

❖ Processos a frio





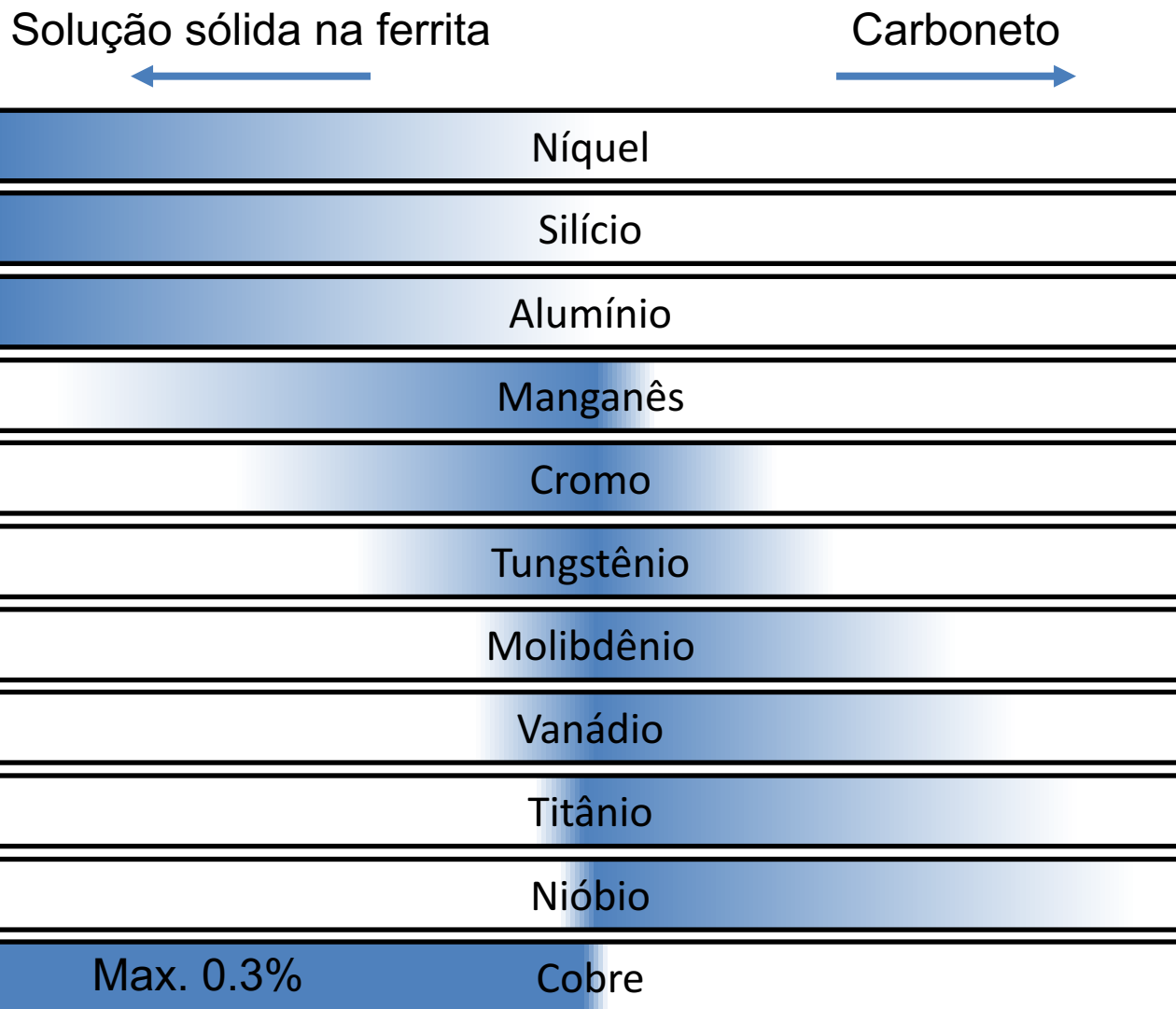
Ligas metálicas e precipitados

- ❖ Elementos de liga são utilizadas para obter certas propriedades e características:
 - ❖ **Melhoria de propriedades mecânicas**
 - ❖ **Melhoria da temperabilidade**
 - ❖ **Maior usinabilidade, resistência ao desgaste e à fadiga**
 - ❖ **Melhoria de resistência à corrosão e oxidação**
 - ❖ **Melhoria de propriedades mecânicas a baixas e/ou altas temperaturas**

- ❖ Ligas de Ferro
 - ❖ **Si, Ni, Nb, Cr, Mo, Mn, V, W, Ti, Al**

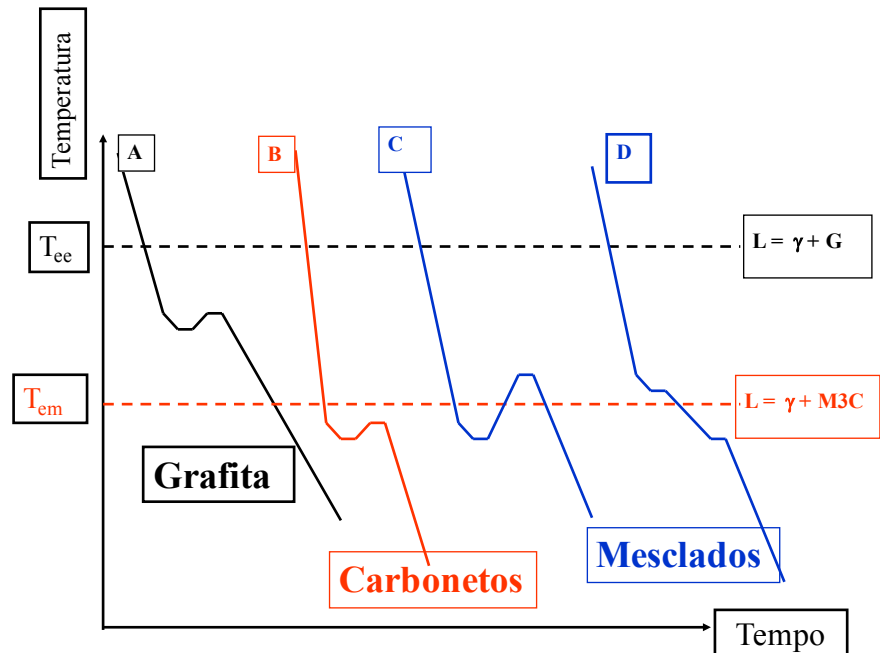
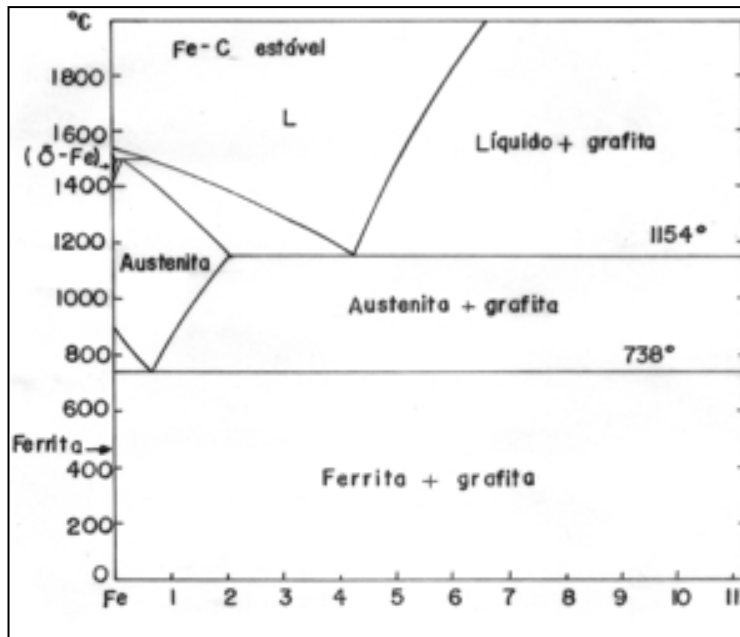
- ❖ Ligas de Alumínio
 - ❖ **Si**

Ligas metálicas e precipitados



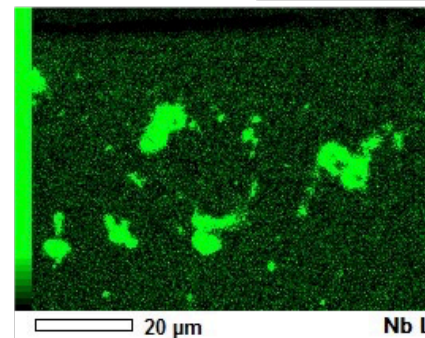
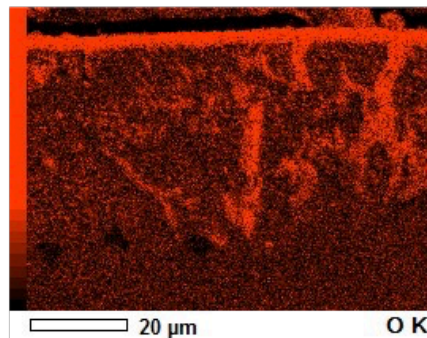
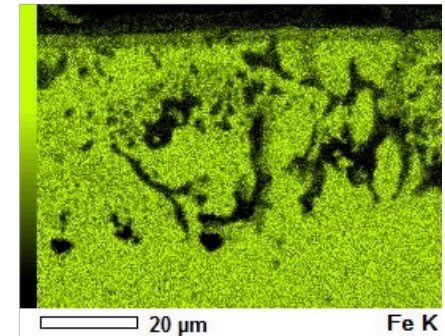
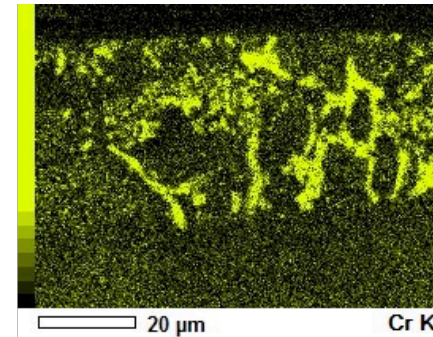
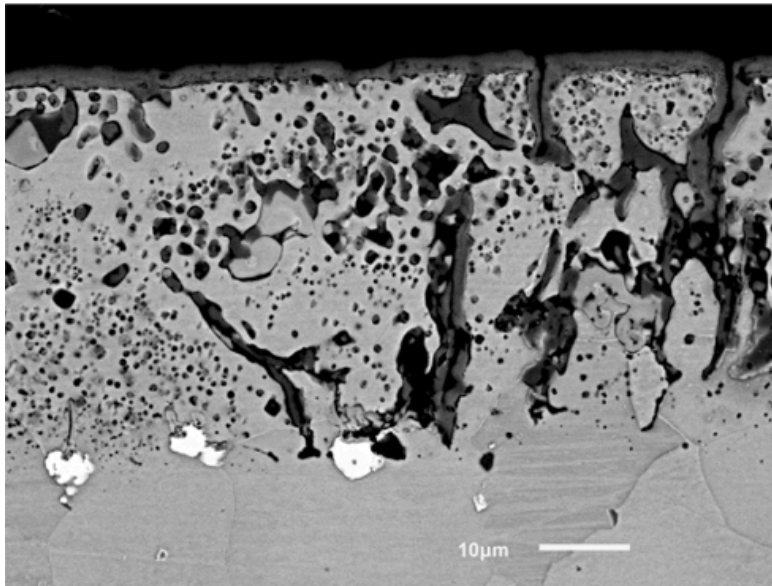
Ligas metálicas e precipitados

- ❖ Carbono equivalente em ferros fundidos
 - ❖ Carbono Equivalente: $CE = \%C + 1/3 \%Si$
 - ❖ **Silício** tem efeito **inoculante**, promovendo a **nucleação de grafita**
 - ❖ **2% Si** aumenta em **29°C** a diferença entre T_{ee} e T_{em}

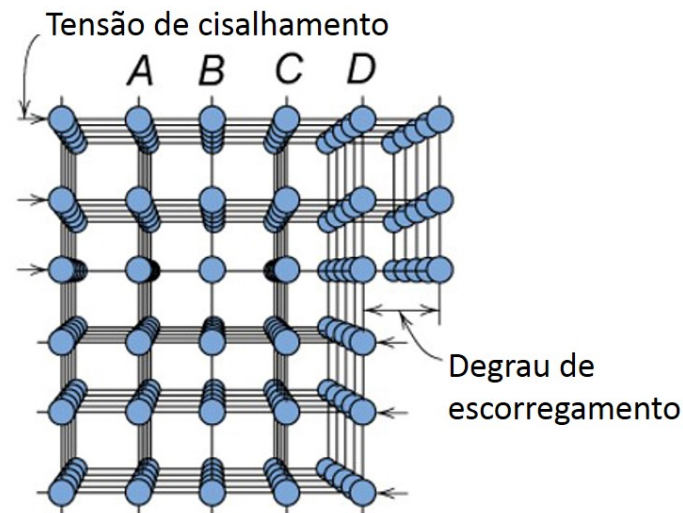
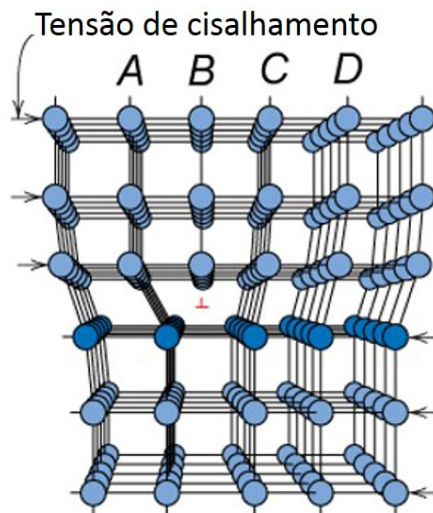
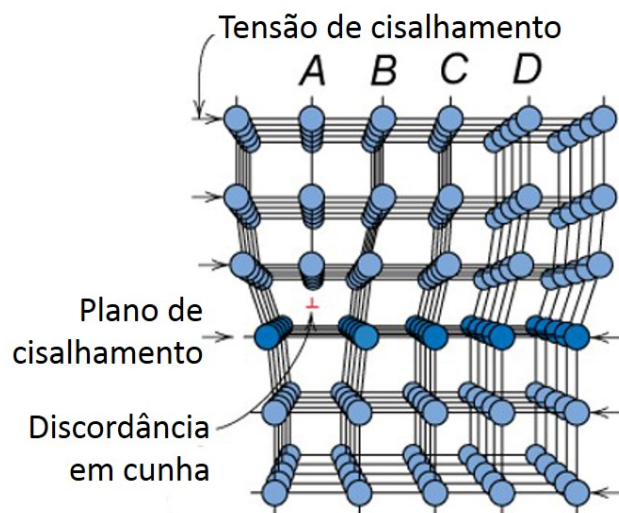
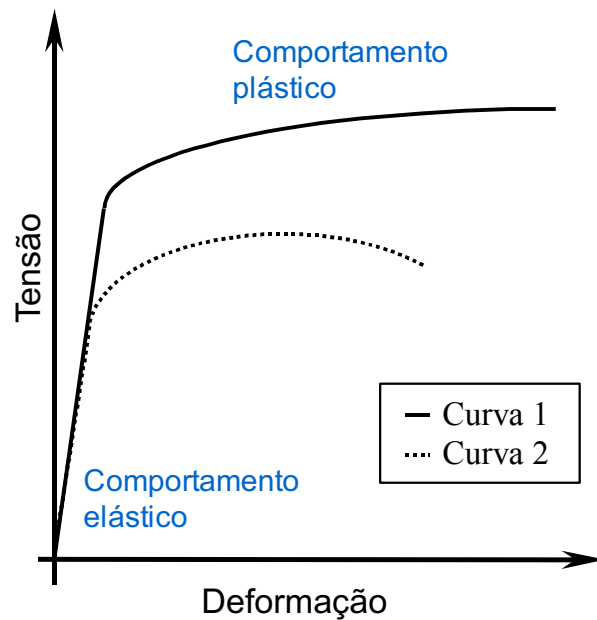
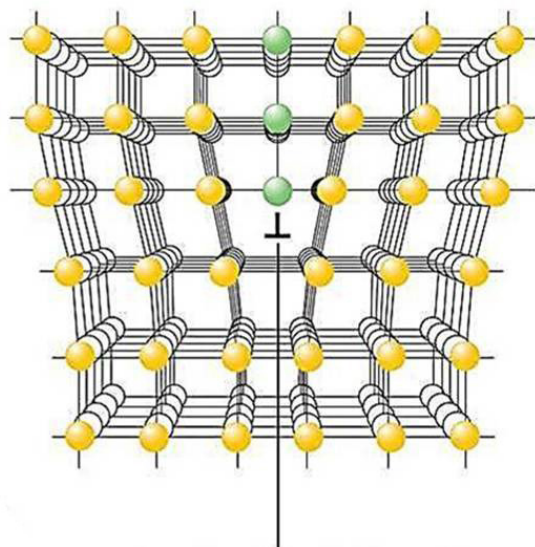


Ligas metálicas e precipitados

❖ Adição de outros componentes



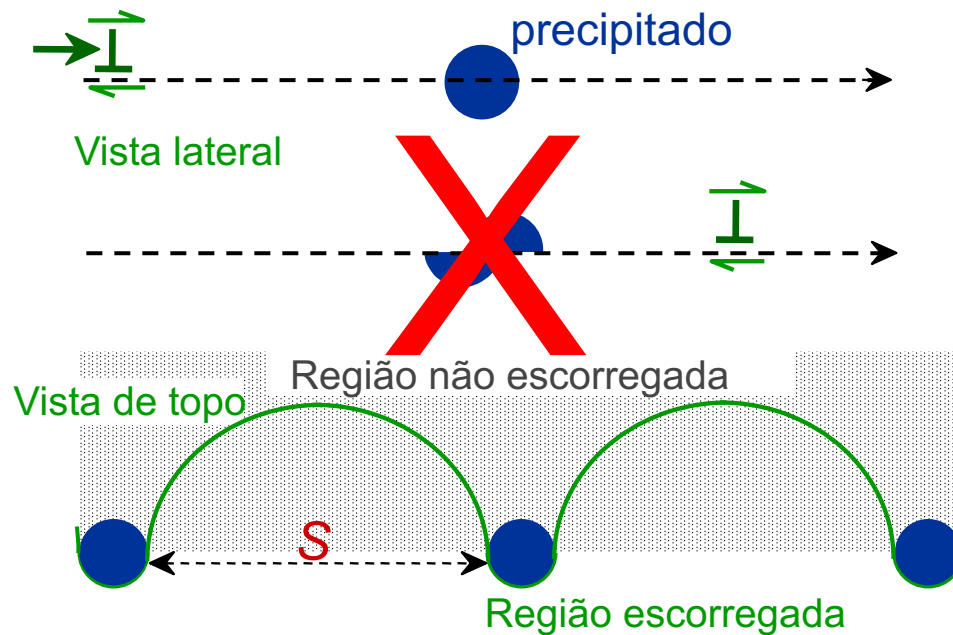
Influência da precipitação



Influência da precipitação

❖ Partículas de segunda fase

- Precipitados duros são difíceis de cisalhar



Altas tensões de cisalhamento são necessárias para mover discordâncias em **direção ao precipitado** e para **cisalhá-lo**

Precipitados agem como “**locais**” de ancoragem

- Resultado:

$$\sigma_y \sim \frac{1}{S}$$



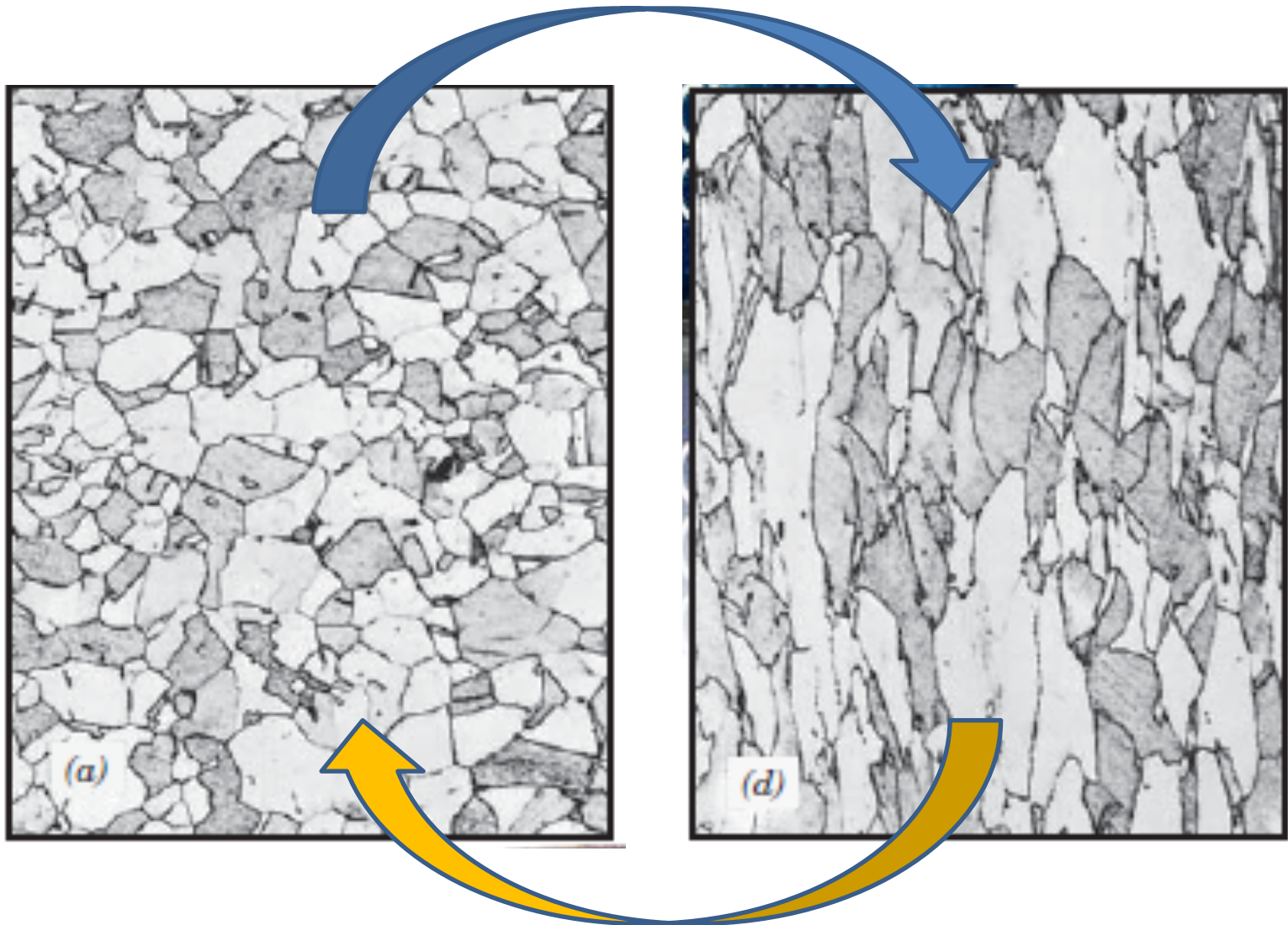
Laminação e forjamento

- ❖ **Se eu quiser laminar, forjar ou estampar a frio, é bom ter precipitados na microestrutura do produto?**
- ❖ **Se for construir uma engrenagem, precipitados são importantes? E a microestrutura?**
- ❖ **Se quiser construir uma mola? Quais as características do meu aço?**

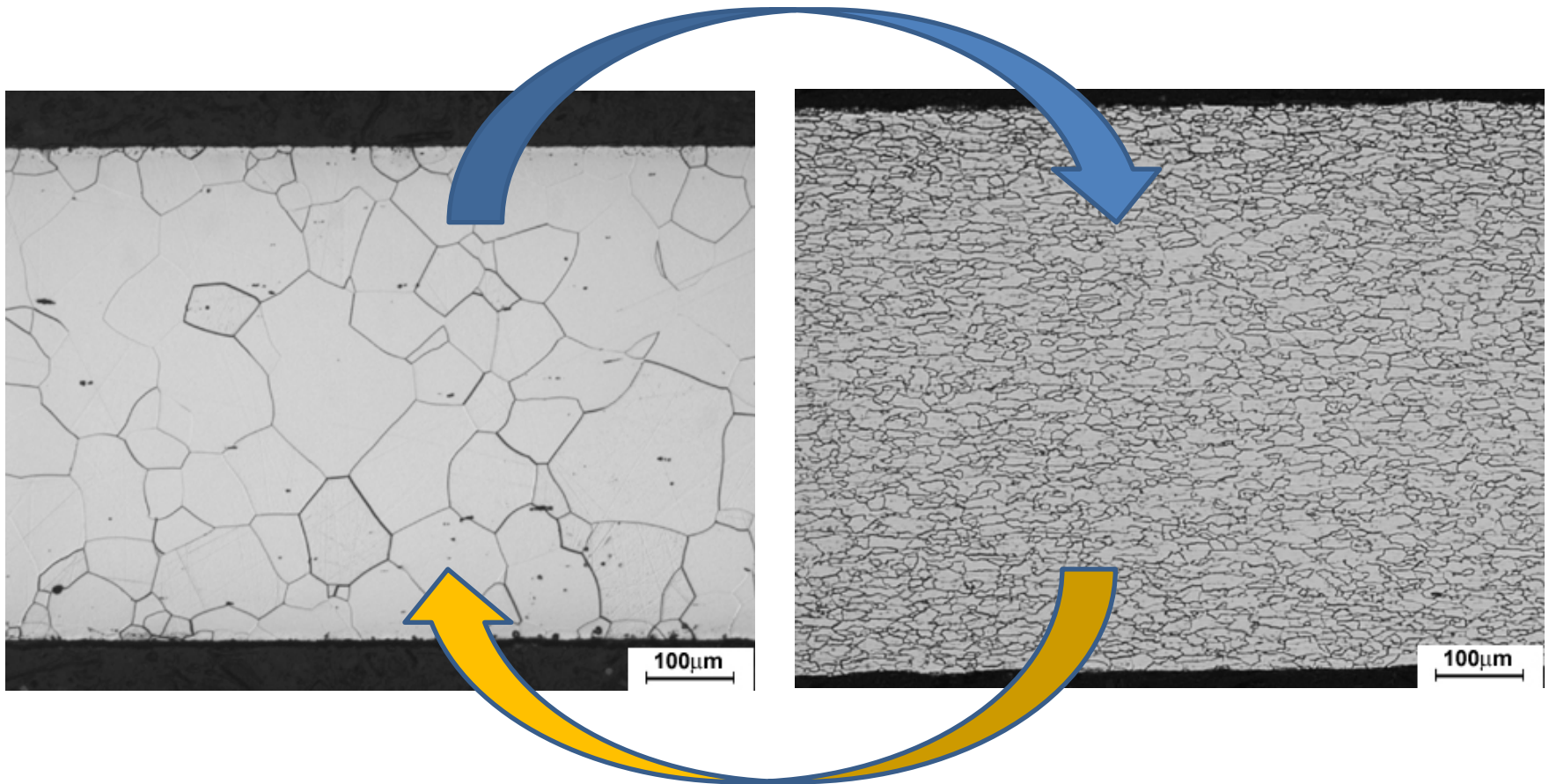


Tratamentos Térmicos

Laminação e Forjamento



Tratamentos Térmicos



Recristalização de grãos – Aços

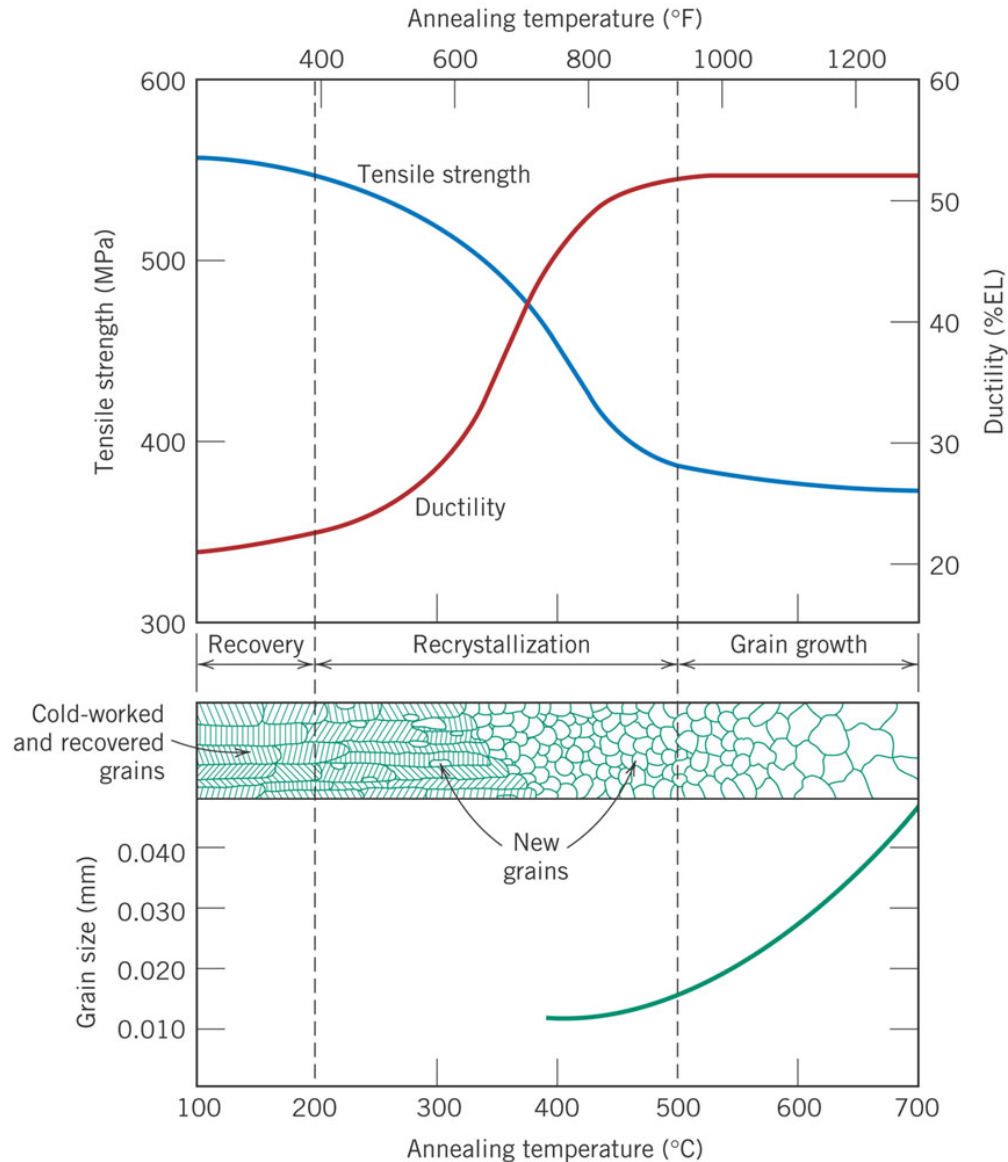
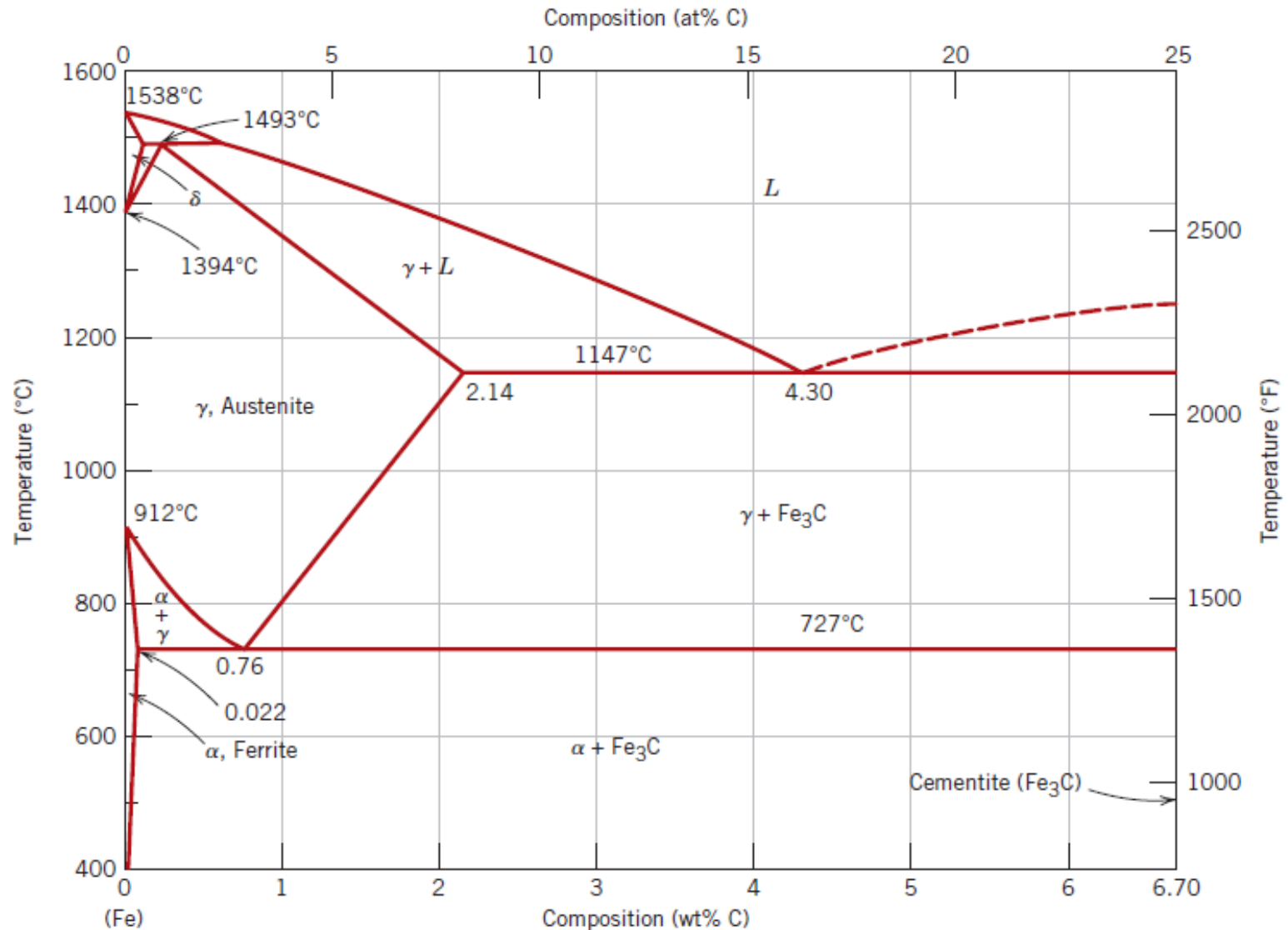




Diagrama de fases – Ferro X Carbono





Tratamentos Térmicos

❖ Austenitização

❖ Processo de aquecimento acima de 727 °C para aços

❖ Depende fortemente da microestrutura do material

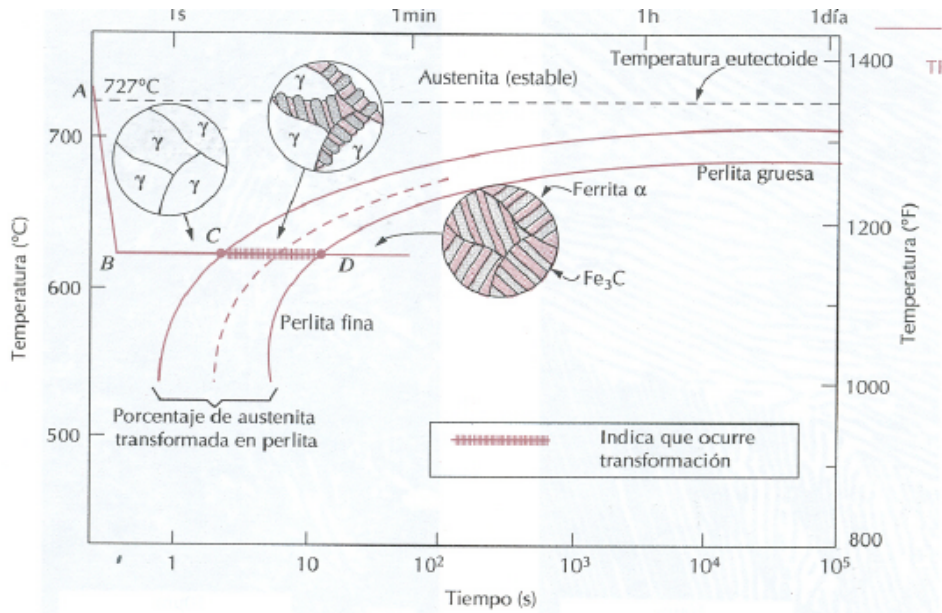
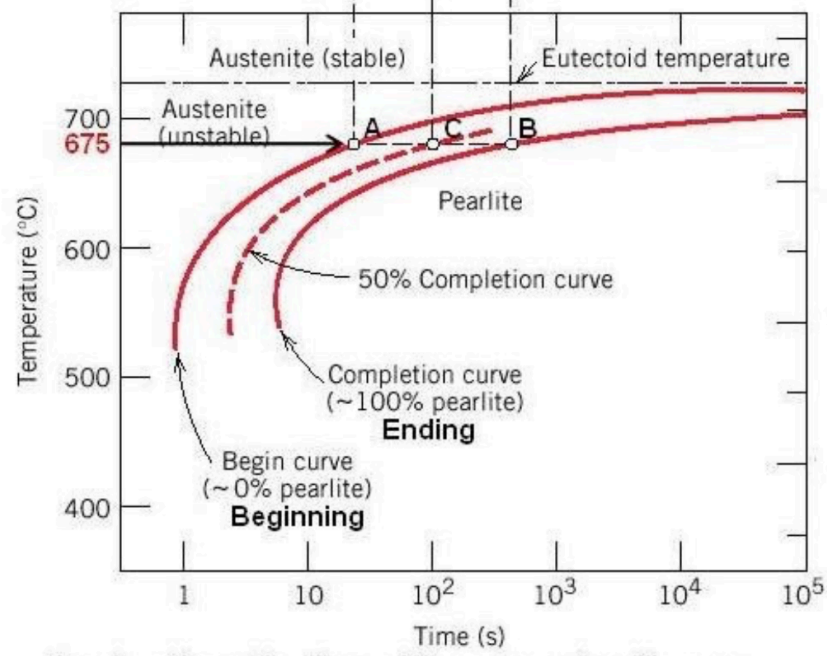
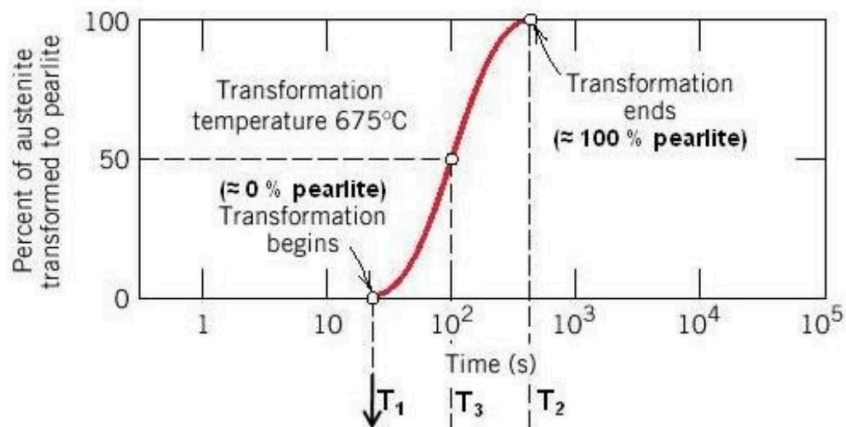
❖ Hipo-eutetóide: perlita -> ferrita + austenita -> austenita

❖ Hiper-eutetóide: perlita -> cementita + austenita -> austenita

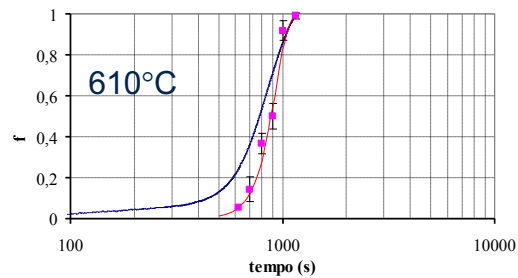
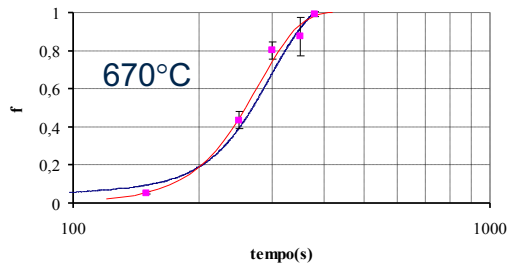
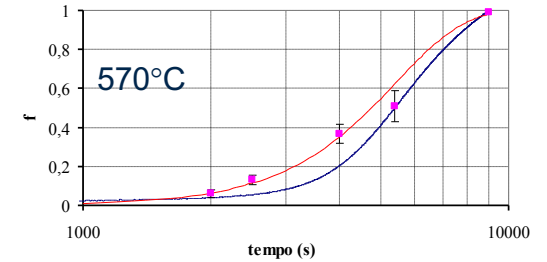
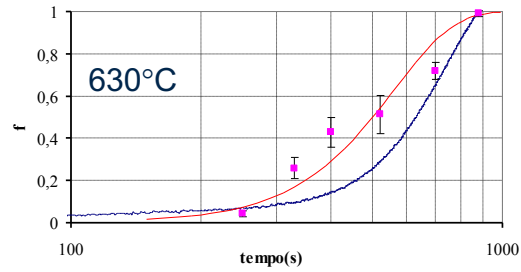
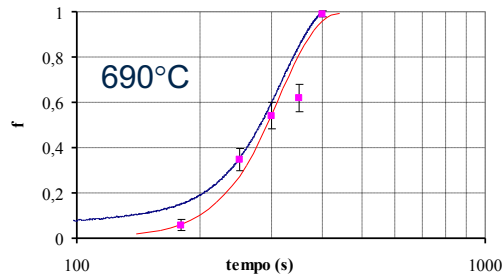
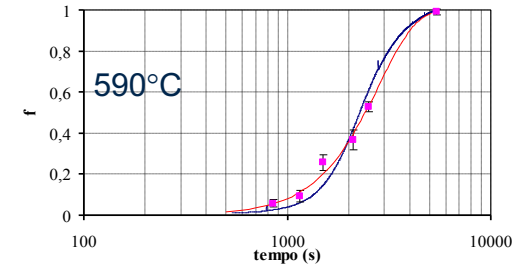
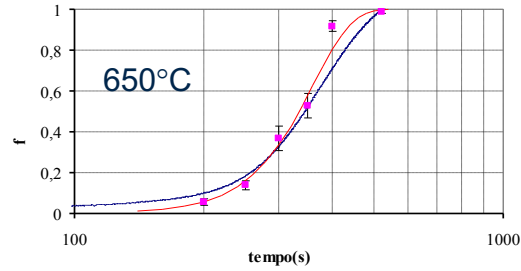
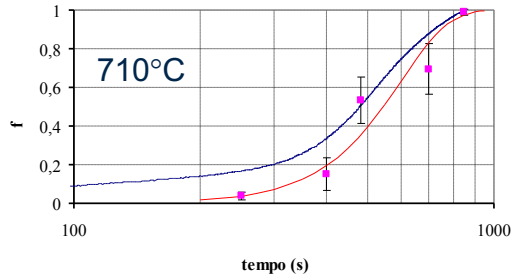
❖ Eutetóide: perlita -> austenita



Tratamiento térmico

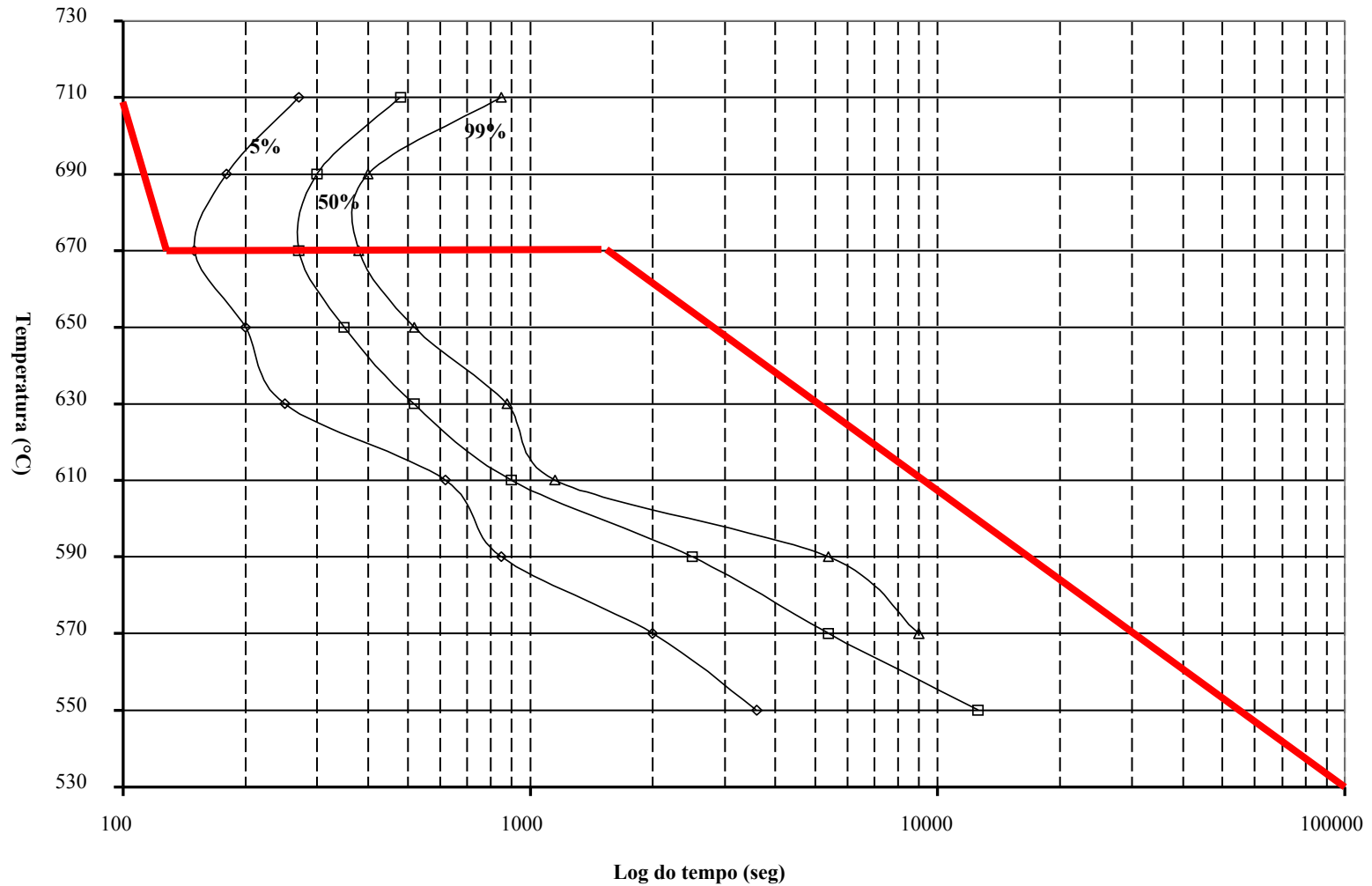


Tratamento térmico



Dilatometria —
Metalografia quantitativa —
JMAK —

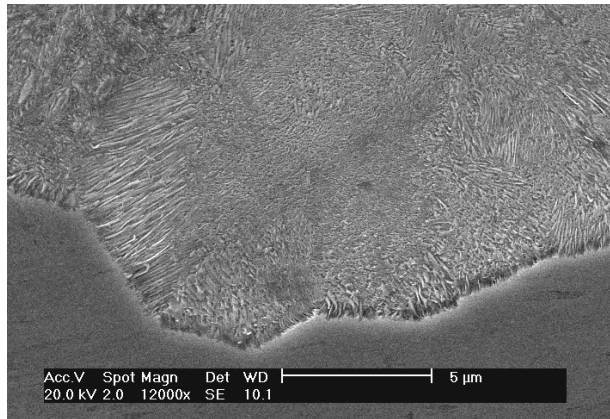
Decomposição da Austenita



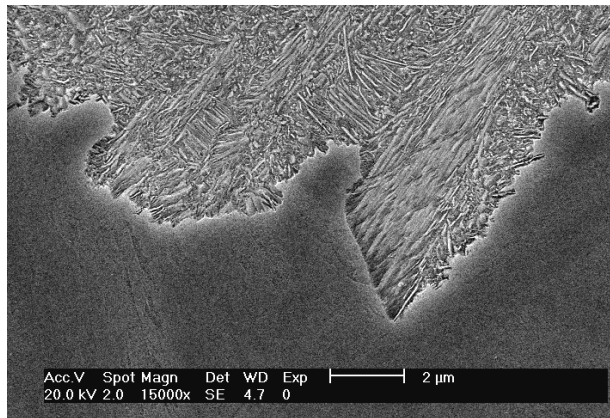
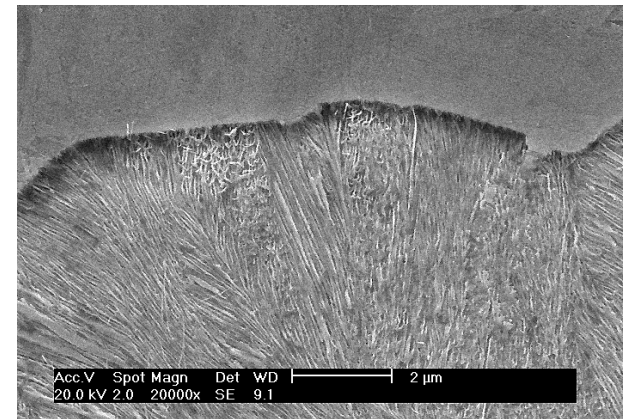
Curva TTT da liga Fe-5,2%Cr-0,46%C.

Decomposição da Austenita

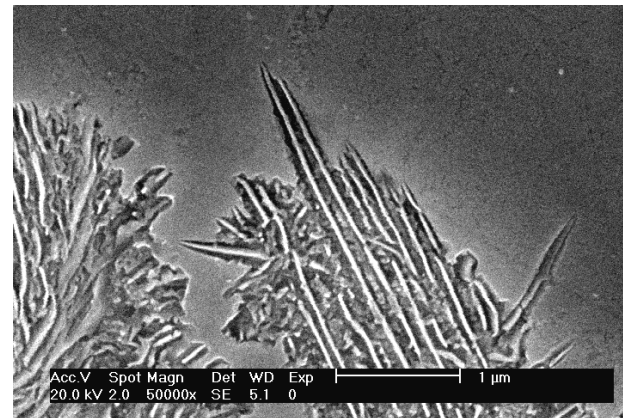
a. 690°C-400s.



b. 670°C-300s.



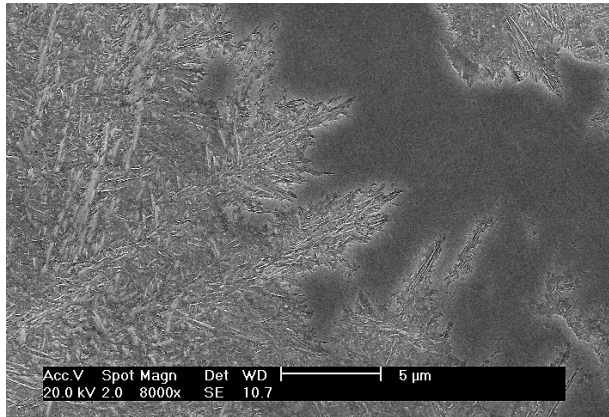
c. 650°C-400s.



d. 650°C-500s.

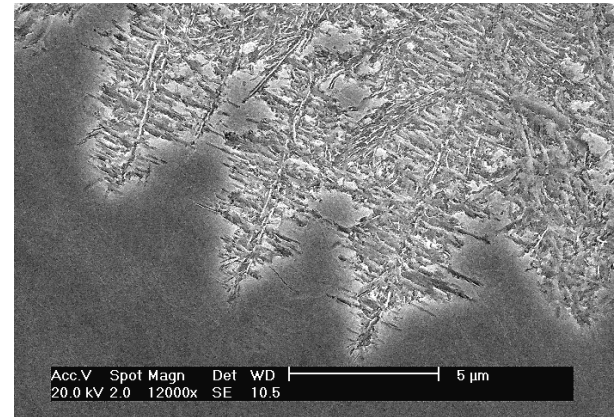
Decomposição da Austenita – Aço Eutetóide

e. 630°C-330s.

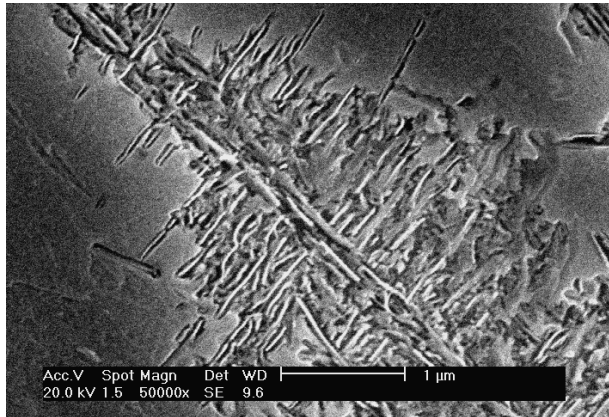


e

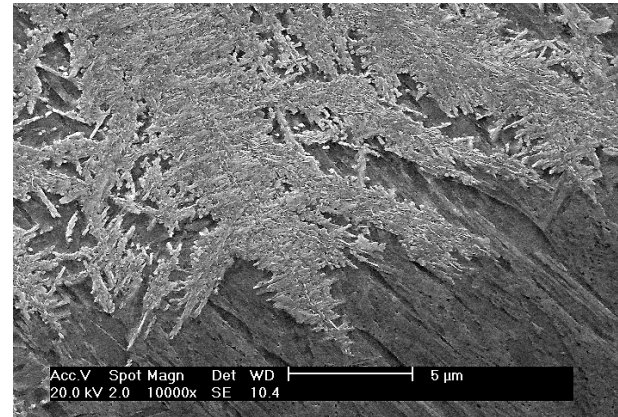
f e g. 610°C-800s.



f



g

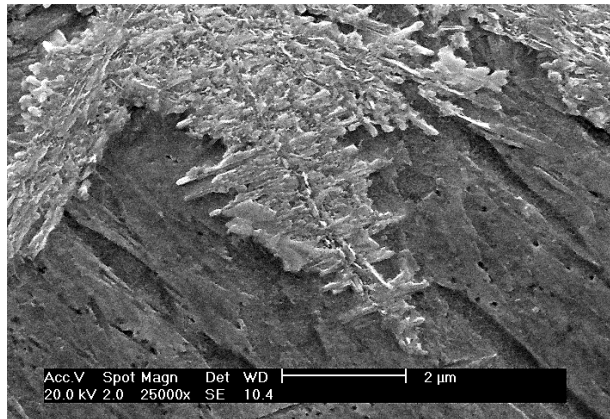


h

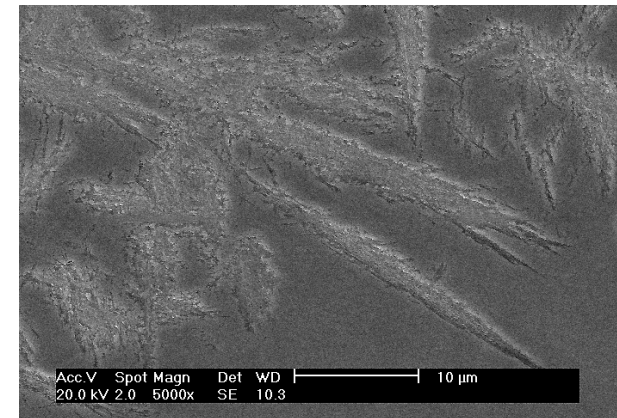
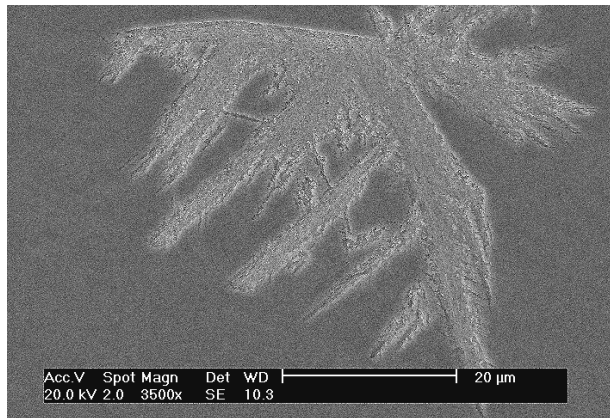
h. 590°C-2500s.

Decomposição da Austenita – Aço Eutetóide

i. 590°C-2500s.



J e k. 570°C-2500s.



l. 550°C-3600s.

Tratamento térmico

❖ Dureza

❖ Austenita

❖ Hv: 150 ~ 200

❖ Ferrita

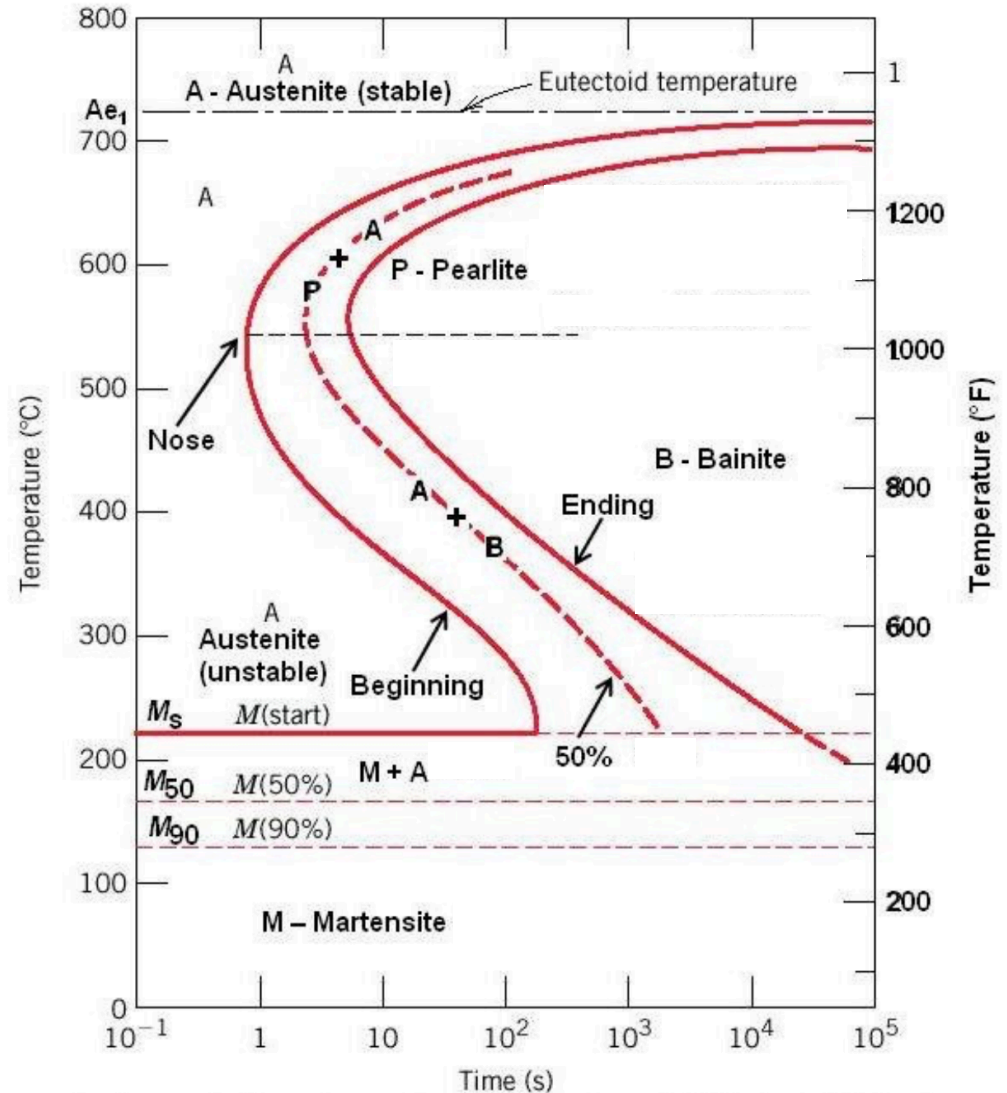
❖ Cementita

❖ Perlita

❖ Meta-estáveis

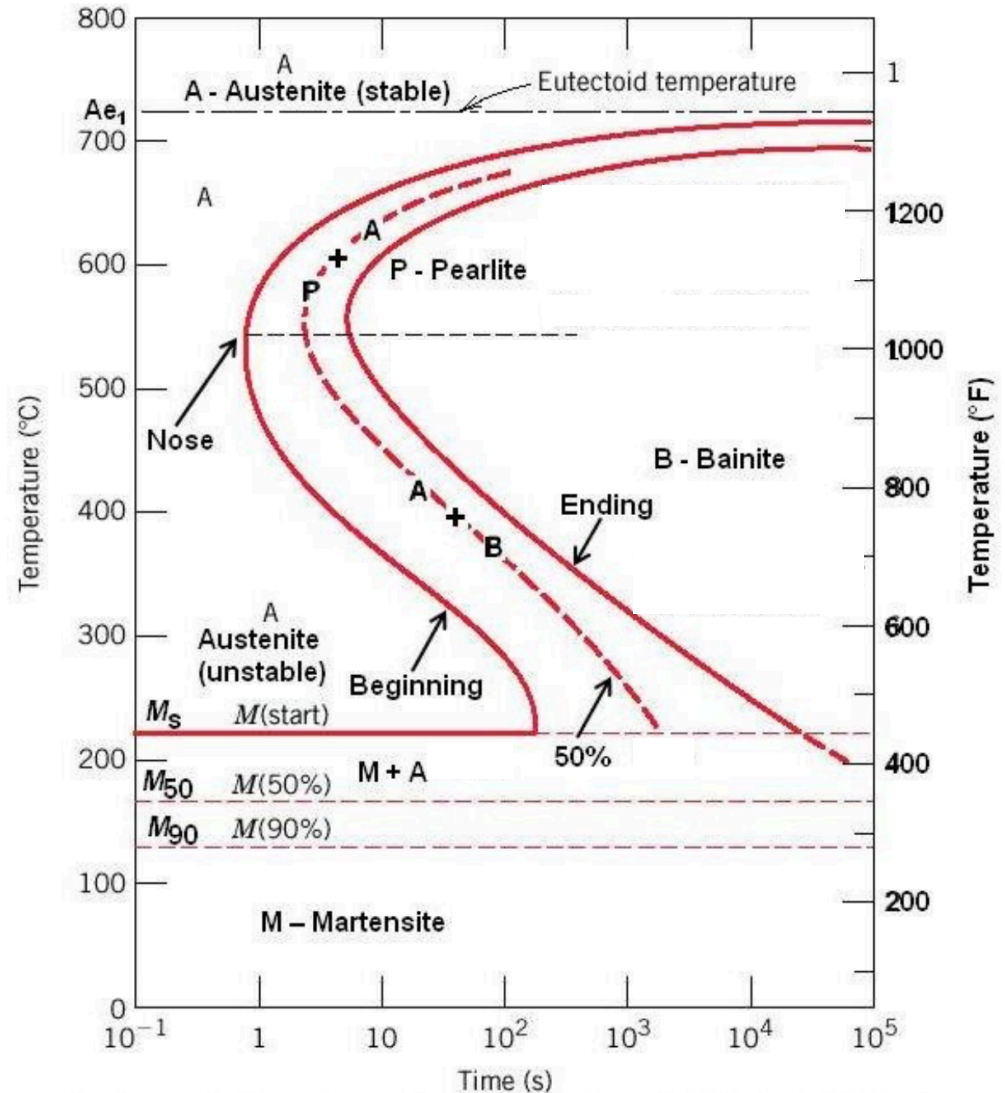
❖ Bainita

❖ Martensita



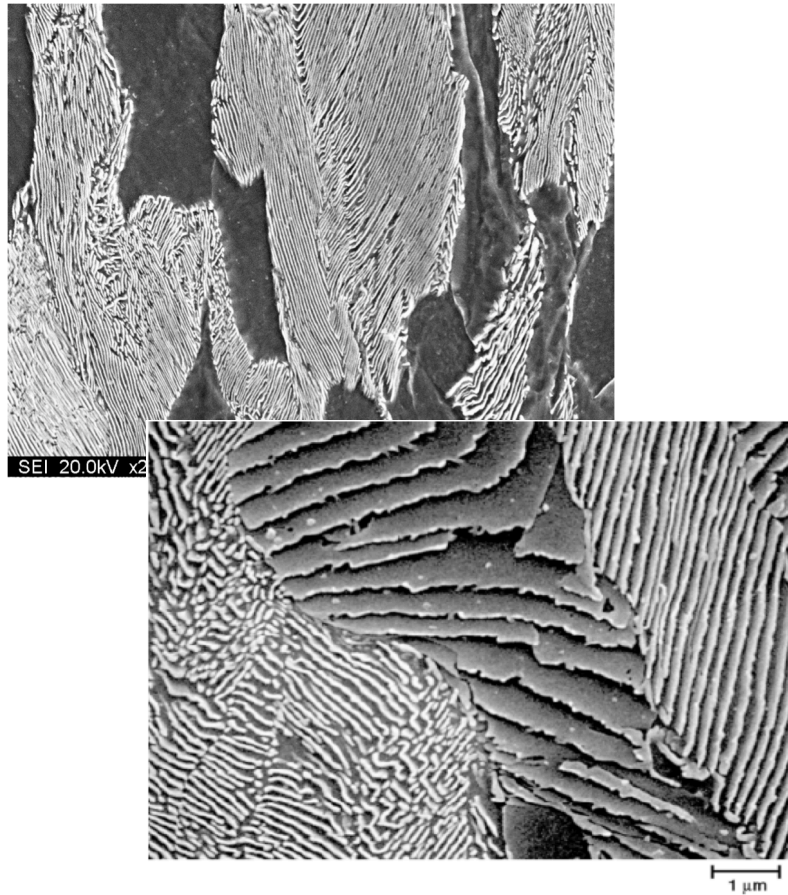
Tratamento térmico

- **Curva mais à esquerda** – início da transformação.
- **Curva mais à direita** – fim da transformação
- Fases:
 - **Antes da curva (Austenita).**
 - **Depois da curva $\alpha + \text{Fe}_3\text{C}$ (Ferrita + Cementita)**
- Acima do cotovelo 550 °C
 - $\gamma = \alpha + \text{Fe}_3\text{C}$ (Perlita)
- Abaixo do cotovelo
 - $\gamma = \alpha + \text{Fe}_3\text{C}$ (Bainita)
- Maior temperatura de transformação
 - **Temperatura eutetóide = 727 °C**
- Menor distância entre eixo Y e a curva:
 - **Temperabilidade (tp = 1s)**
- Temperatura de início de martensita
 - **M_s (Martensite Start) = 220 °C**

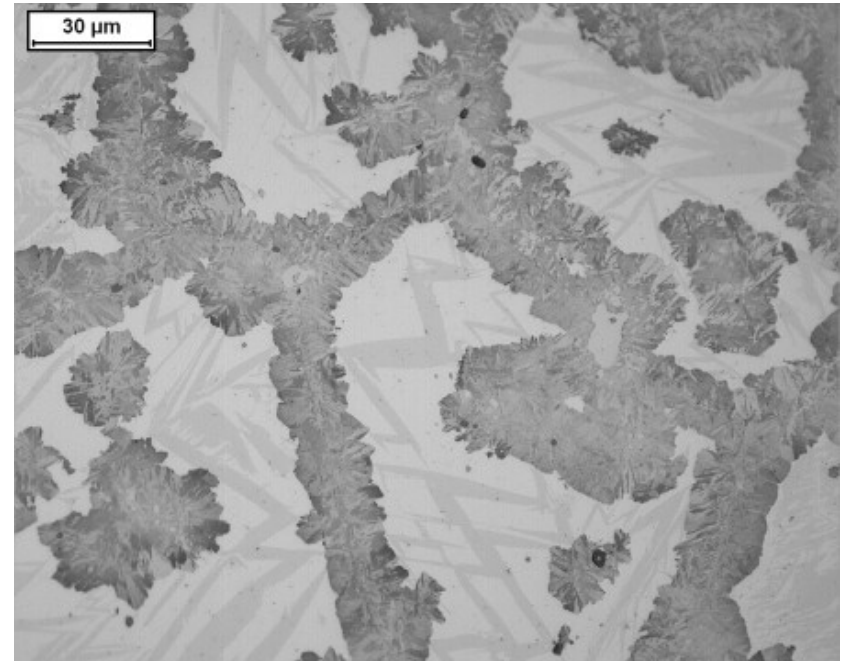


Tratamento térmico

Perlita



Bainita

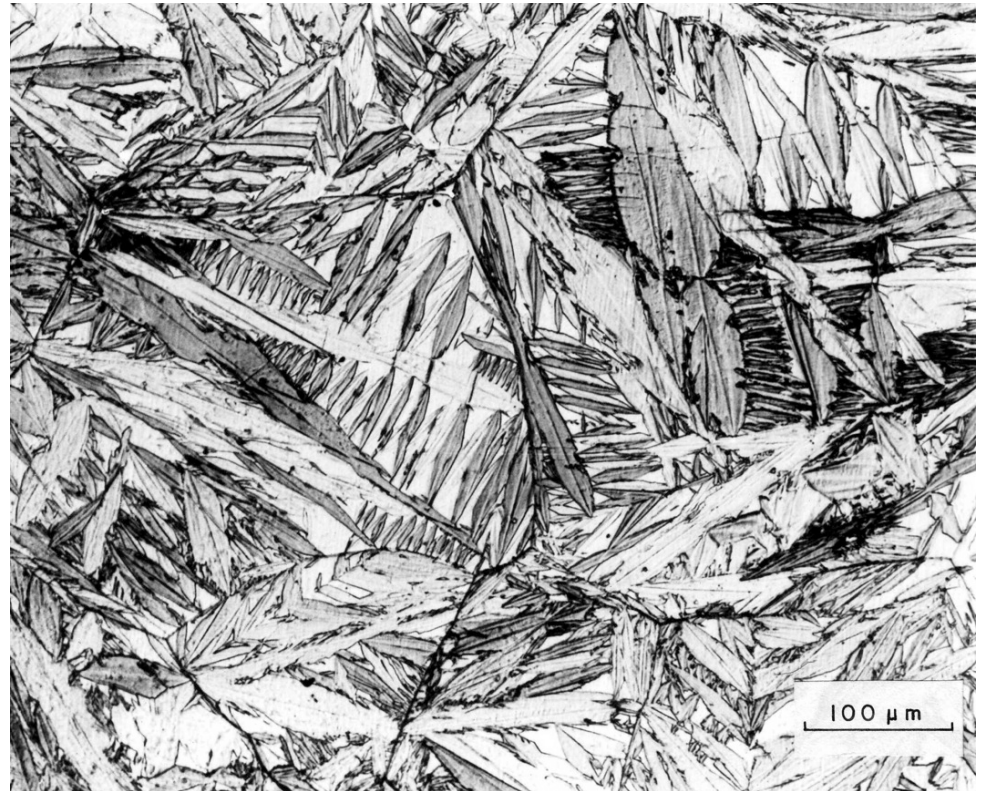


<http://www.hero-m.mse.kth.se/page.php?pid=137>

Tratamento térmico

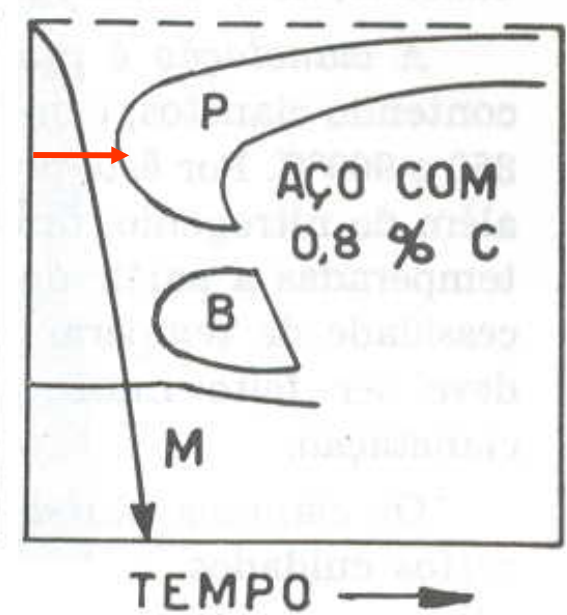
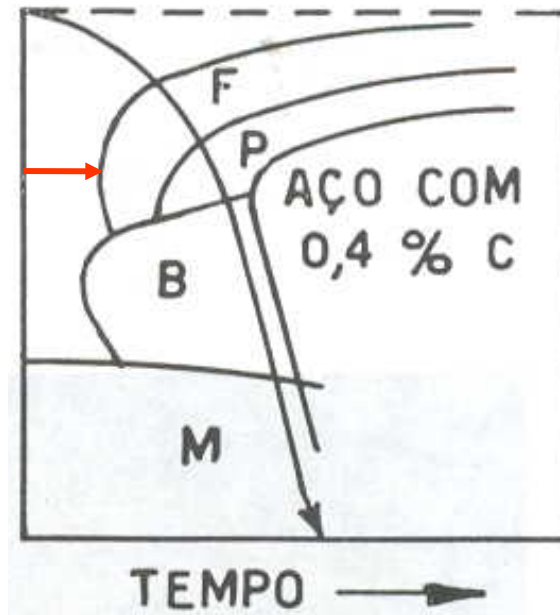
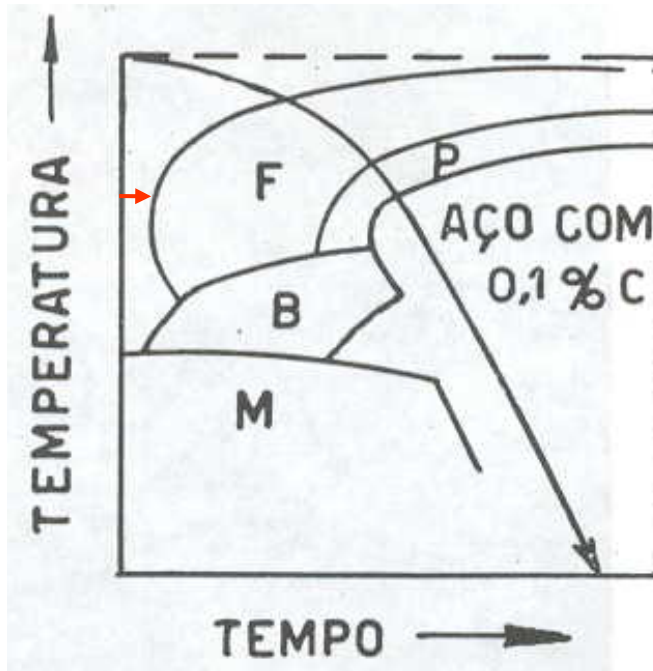
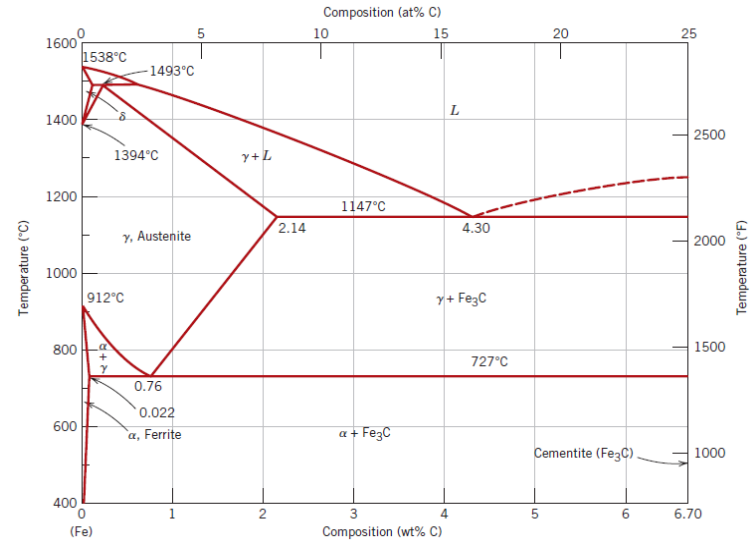
❖ Martensita

- ❖ Tetragonal de Corpo Centrado
- ❖ Formada a partir da austenita
- ❖ Meta-estável
- ❖ Quantidade de martensita formada depende da temperatura e não do tempo



Tratamentos Térmicos

❖ %C altera o TTT



Tratamento térmico

❖ Dureza

❖ Austenita

❖ Hv: 150 ~ 200

❖ Ferrita

❖ Hv: 180 ~ 280

❖ Cementita

❖ Hv: 350 ~ 480

❖ Perlita

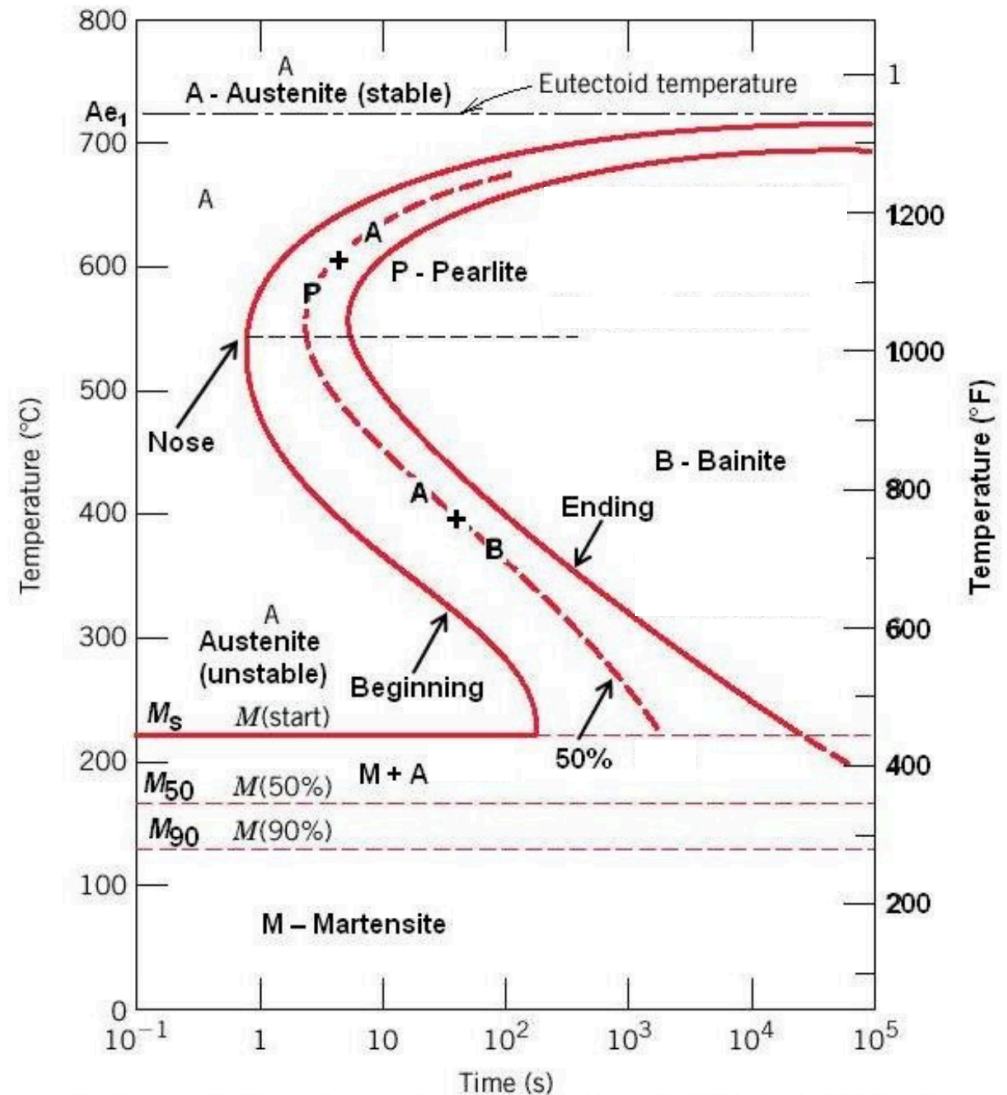
❖ Hv: 250 ~ 300

❖ Bainita

❖ Hv: 500 ~ 800

❖ Martensita

❖ Hv: 700 ~ 1200





Tipos de Tratamentos Térmicos

- ❖ **Têmpera**
- ❖ **Revenimento**
- ❖ **Austêmpera**
- ❖ **Recozimento**

Tratamentos Térmicos

❖ Têmpera

❖ Formação de martensita

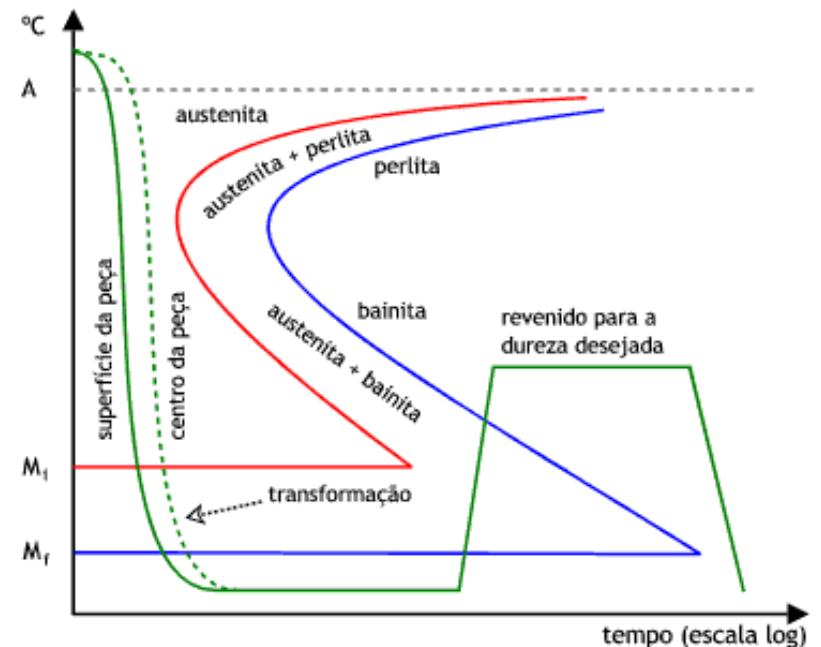
❖ Aumento de dureza do material

❖ Diminuição da ductilidade

❖ Revenimento

❖ Alívio de tensões

❖ Aumento de ductilidade



<http://www.msps.eng.br/ciemat/aco130.shtml>



❖ Pode apresentar melhores propriedades mecânicas comparada à tempera + revenimento



Tratamentos Térmicos

❖ Recozimento

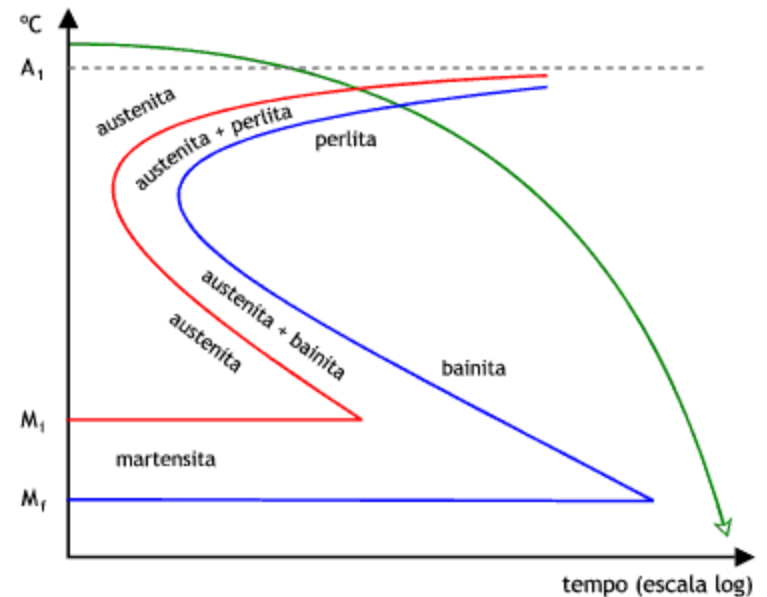
❖ Restaurar as condições iniciais

❖ Diminuir as tensões residuais

❖ Aumentar tamanho de grão

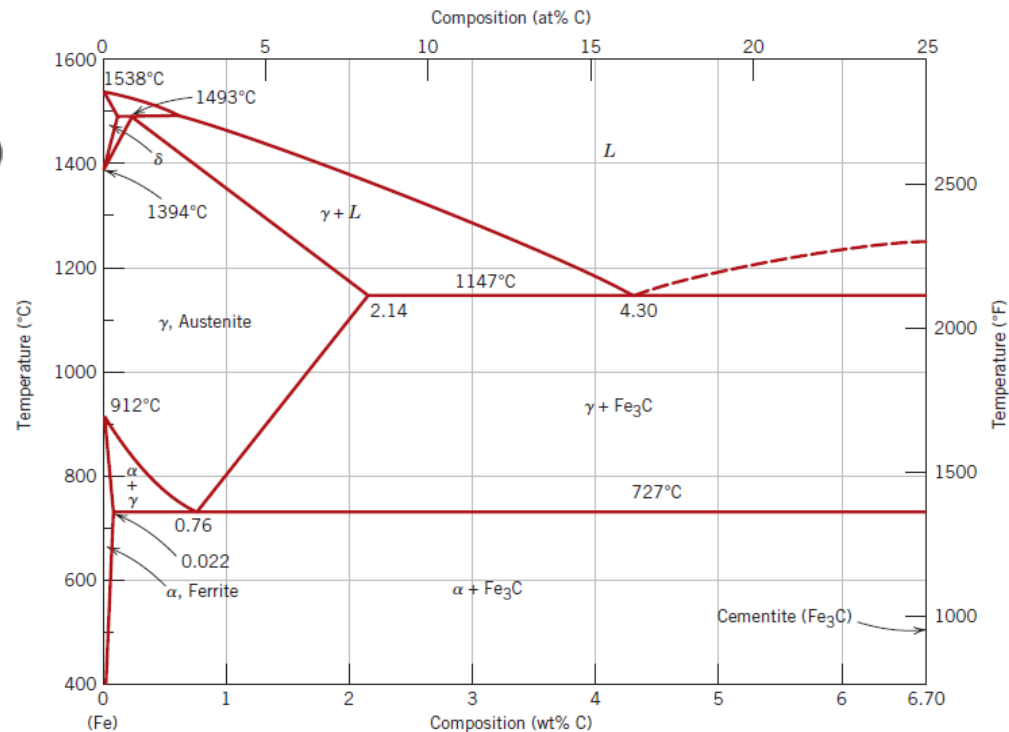
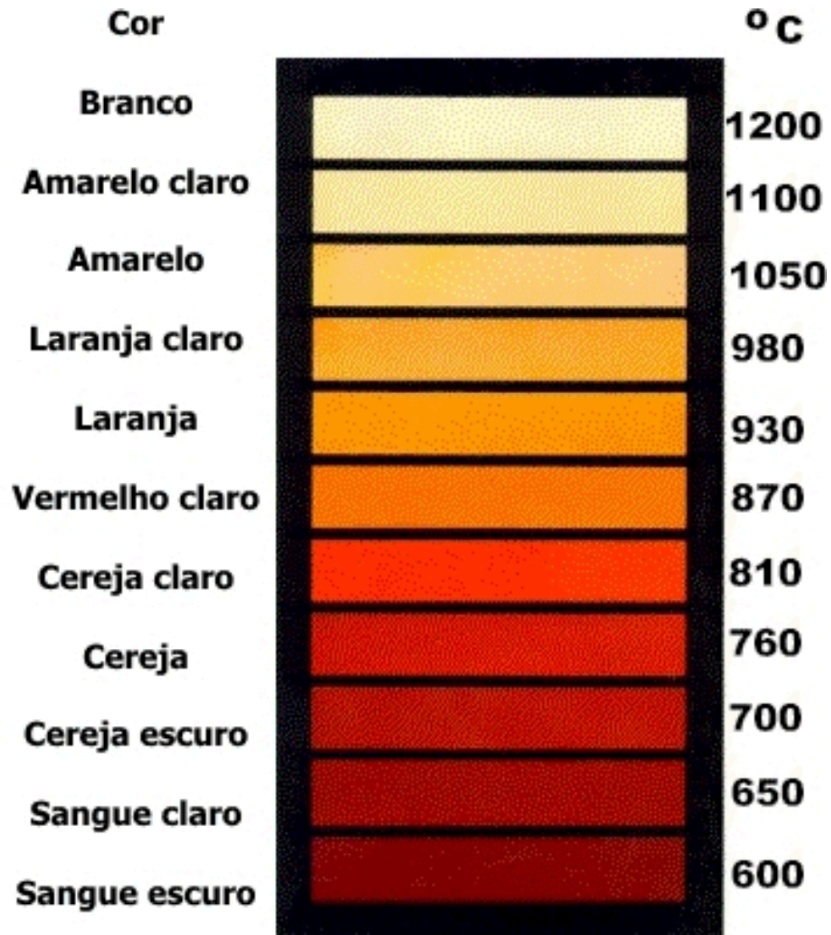
❖ Aumentar a ductilidade

❖ Aumentar a usinabilidade



<http://www.mspc.eng.br/ciemat/aco130.shtml>

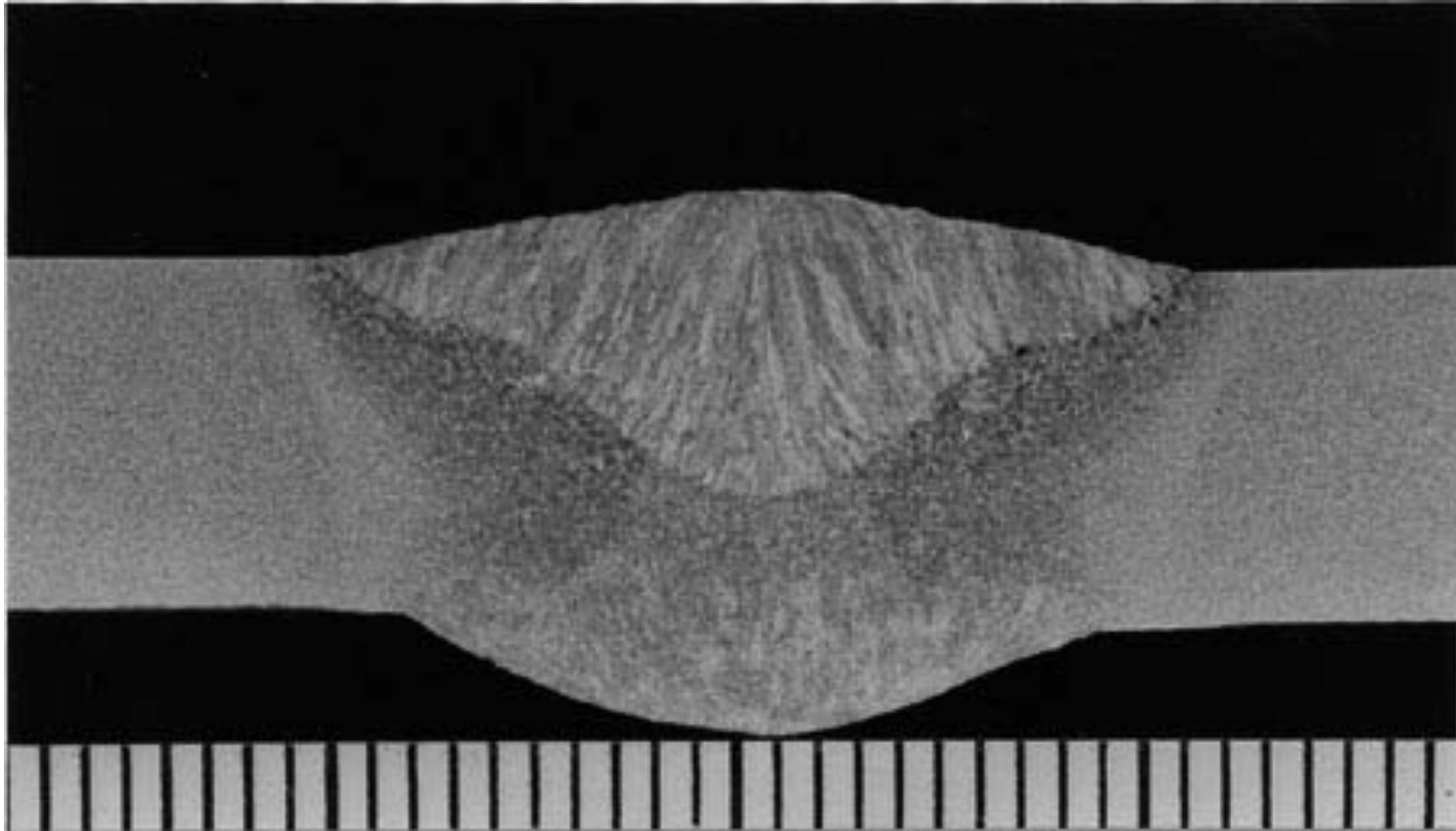
Tratamentos Térmicos





Processos com Tratamento Térmico

❖ **Soldagem**



<http://www.kobelco-welding.jp/portuguese/education-center/medium/medium02.html>