

# SMM0330-PRINCÍPIOS DE ANÁLISE DE FALHAS EM COMPONENTES



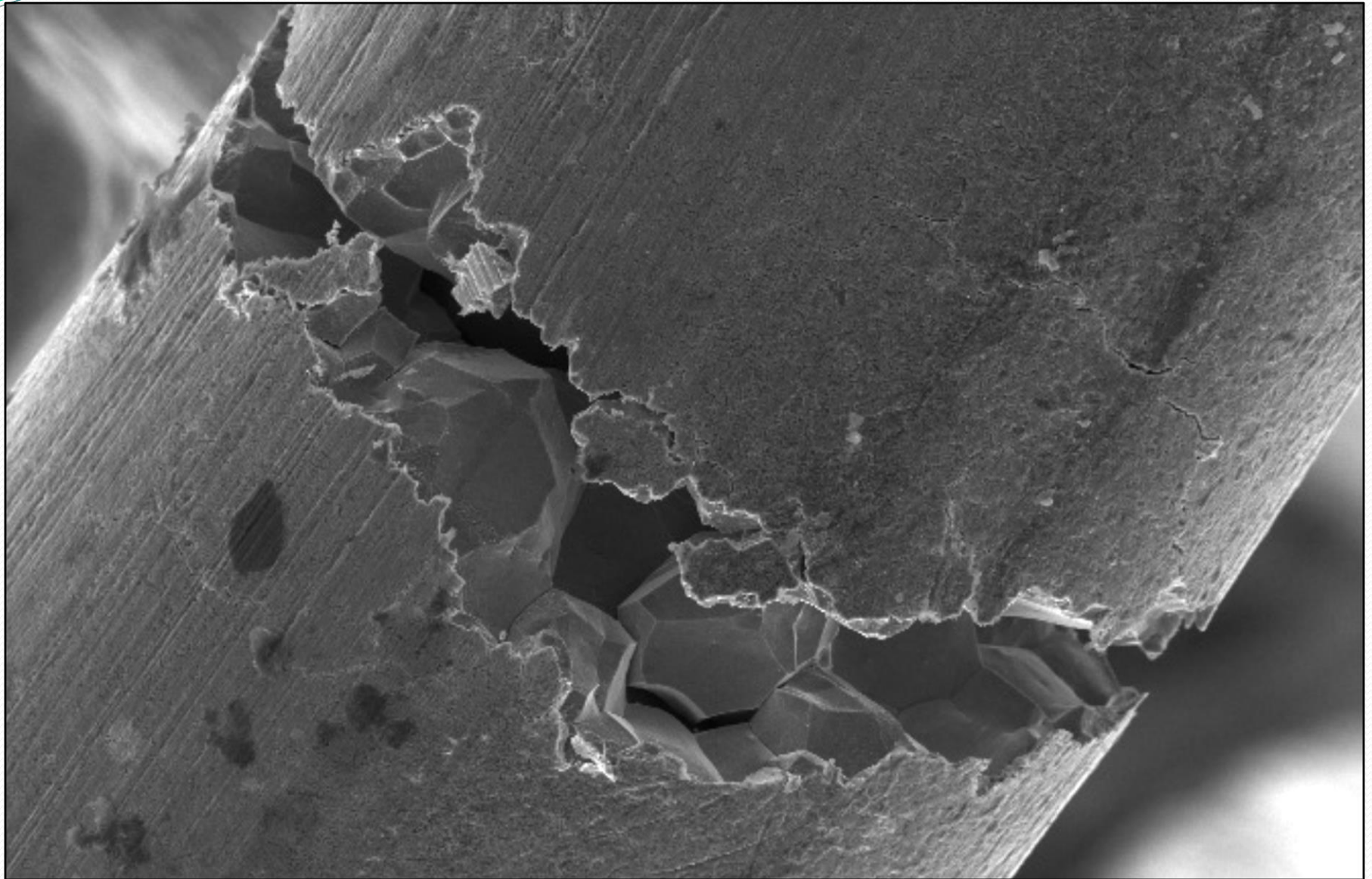
**Prof.Dr. José Benedito Marcomini**

## **REFERÊNCIAS:**

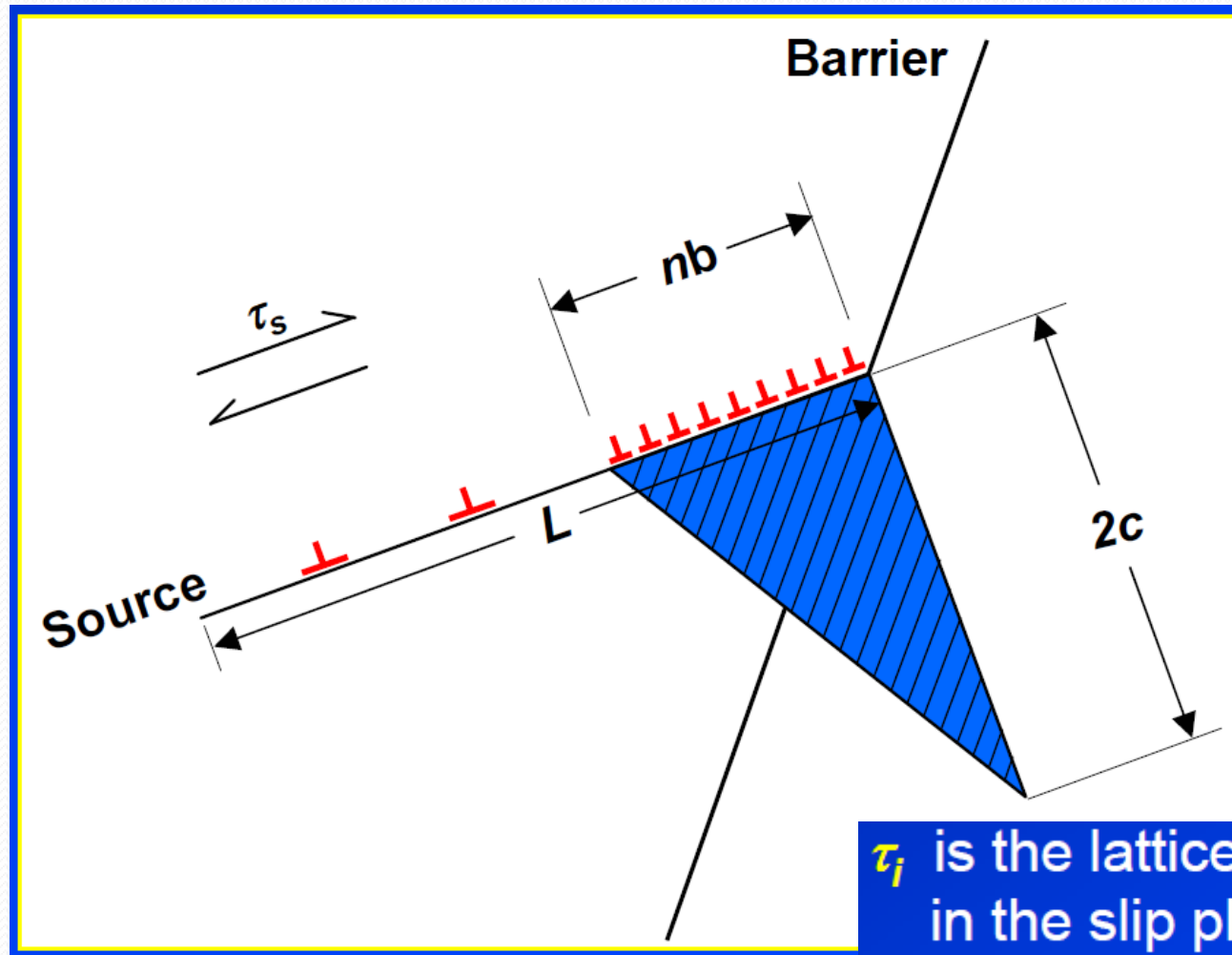
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- **Mecânica dos Materiais**, Claudio Geraldo Schön, Elsevier, 2013.
- **Apostila do curso Mecânica de Fratura Elasto-Plástica**, Cláudio Ruggieri, EPUSP, 2010;
- **Apostila do curso Fadiga de Materiais Estruturais**, Cláudio Ruggieri, EPUSP, 2010;
- **Relatórios de análise de falhas do Prof. José B. Marcomini.**



- **O micromecanismo de fratura intergranular se refere à propagação da trinca ao longo de contornos de grão;**
- **Facetas dos contornos das superfícies de grãos individuais;**
- **Restrição do movimento das linhas de discordância pelo contorno de grão enfraquecido por precipitação;**
- **Empilhamento de discordâncias gerando a microtrinca (Clarence Zener - “The Micro-mechanism of Fracure” – em *Fracturing of Metals*, American Society for Metals, Metals Park, Ohio, 1948).**



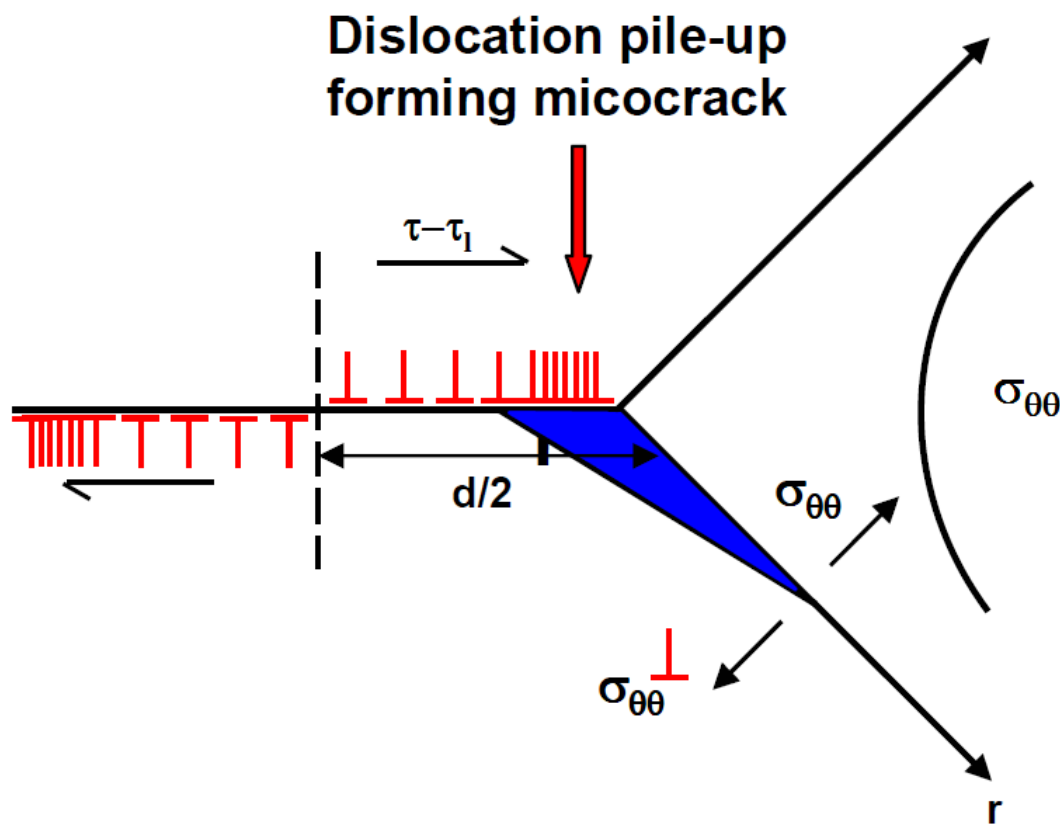
A trinca é nucleada quando  $\tau_s$  satisfaz a relação abaixo

$$\tau_s \approx \tau_i + \left( \frac{2\gamma_s}{nb} \right)$$

**Burgers vector b**

$\tau_i$  is the lattice friction stress in the slip plane.

shear stress  $\tau_s$  created by *pile-up*



$$\tau_{eff} = \tau_y - \tau_i \sqrt{\frac{E\pi\gamma}{4(1-\nu^2)d}}$$

Supondo  $d$  infinito,  $\tau_i$  tende a zero e  $\tau_{eff}$  é igual ao limite de escoamento: fratura transgranular (ex: dimples). Não ocorre a intergranular.

Existem outros modelos, que foram sendo desenvolvidos pela observação em MET. Para ligas multifásicas, o caso é mais complexo que os modelos.

**Stroh** included the effect of the grain size  $d$



**PILE UP EM TRINCA INTERGRANULAR (LATÃO ALFA)**



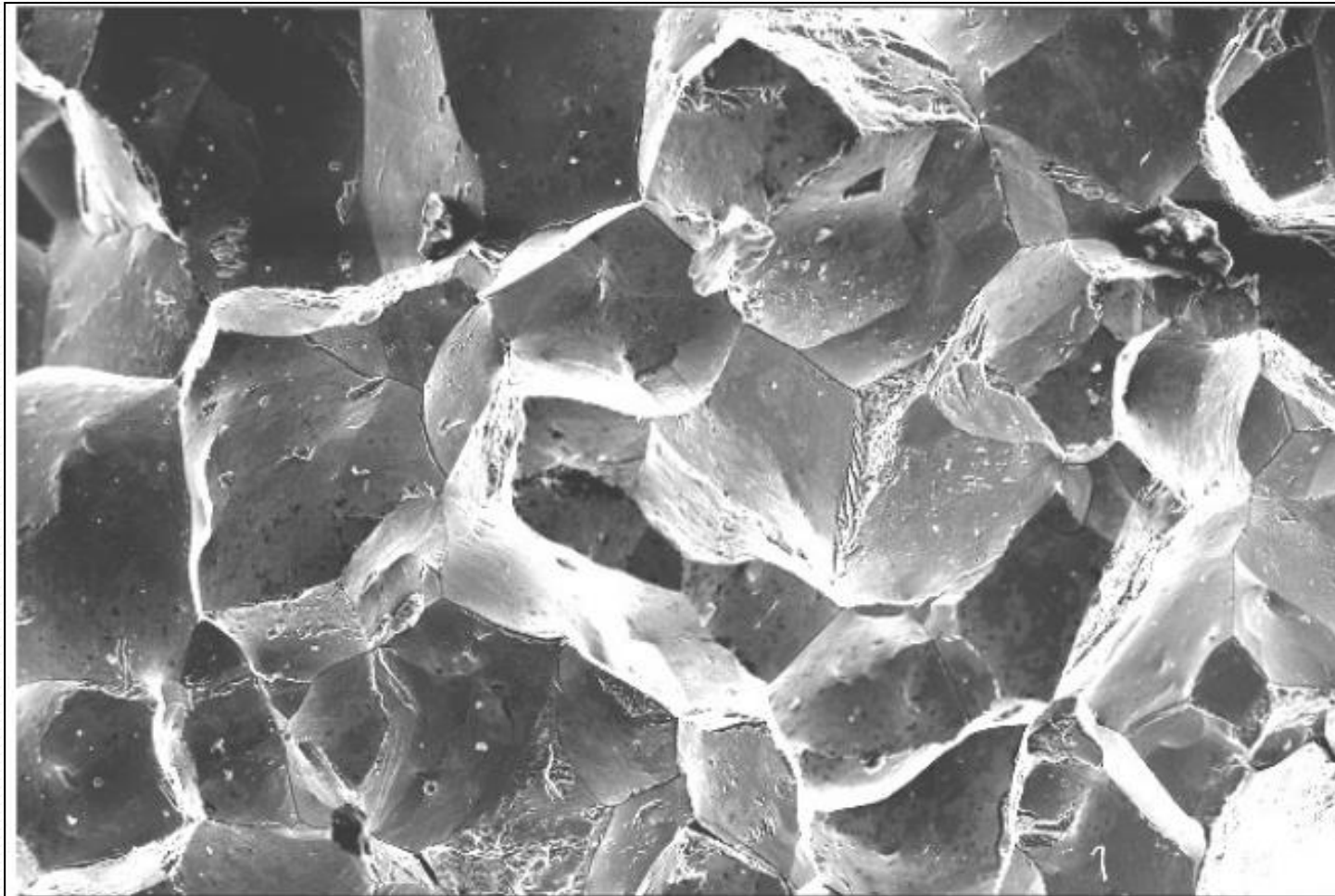


Mag = 120 X  
EHT = 20.00 kV

1mm



Detector = SE1  
Date :31 Mar 2008



Mag = 540 X

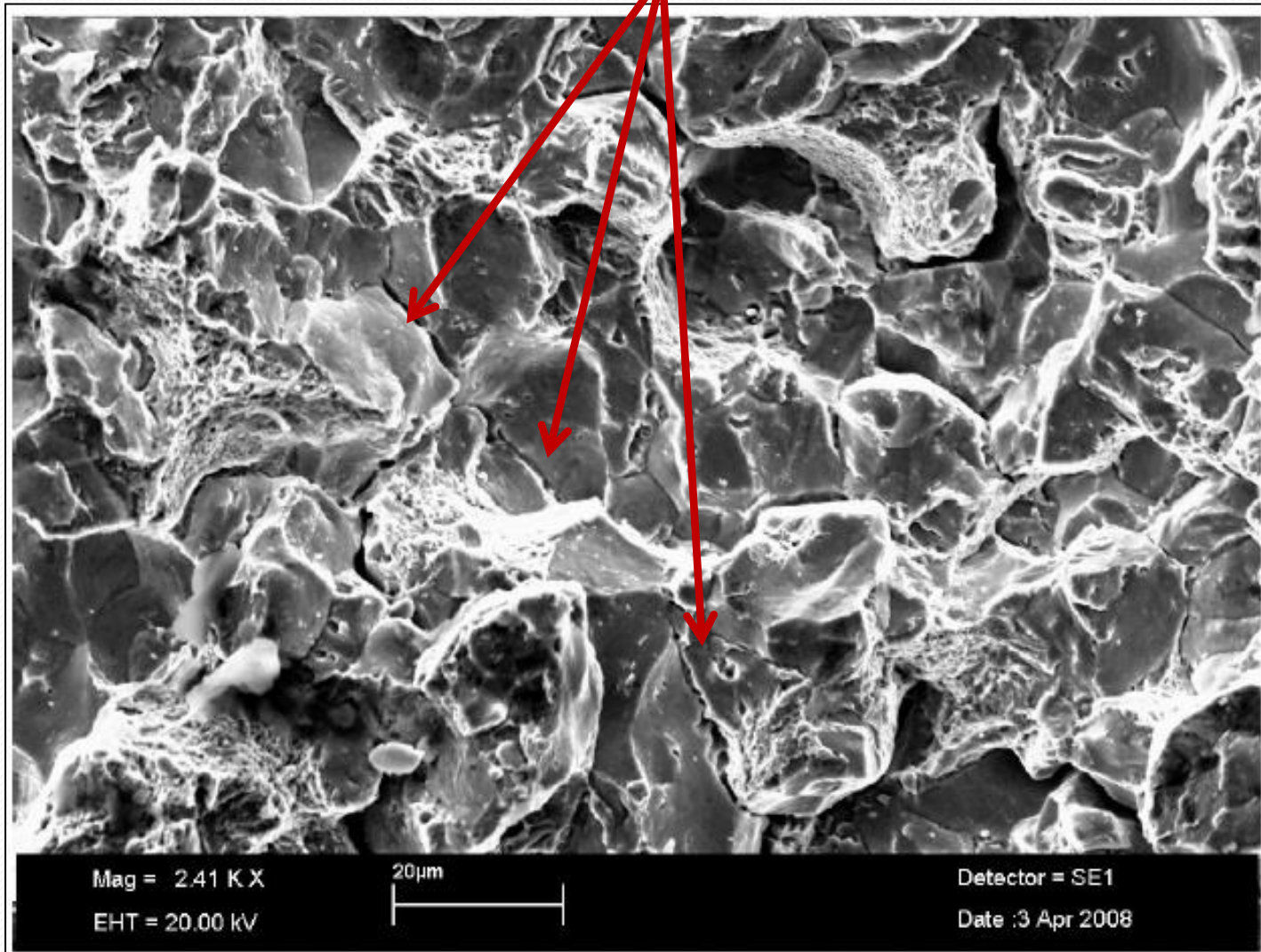
100µm

Detector = SE1

EHT = 20.00 kV

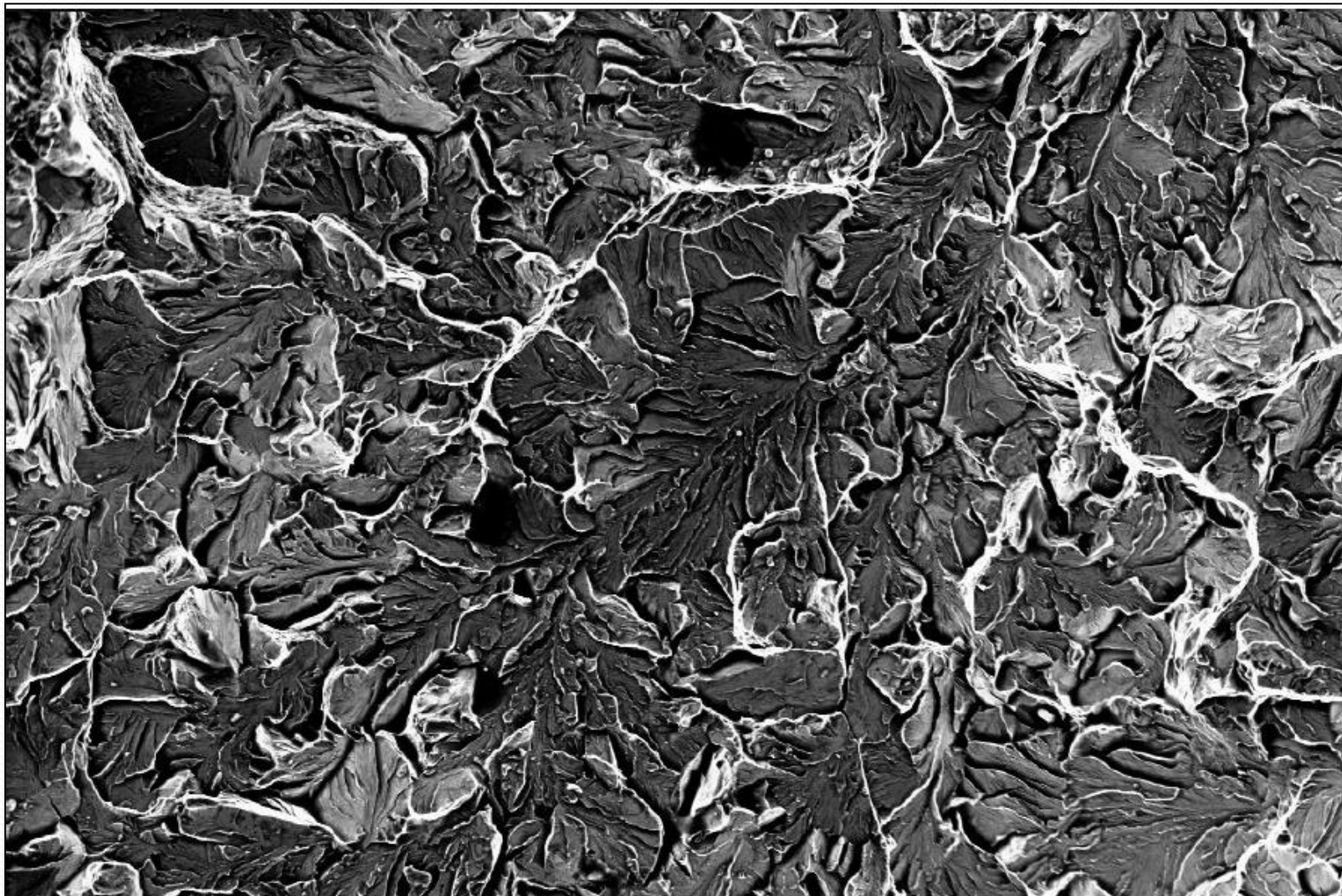
Date :7 Apr 2008

# TRINCAS SECUNDÁRIAS



- **Ocorre ao longo de planos cristalográficos bem definidos;**
- **Ocorre, sob certas condições - CCC - (aços, ferro, cromo etc.) e HC (zinco e berílio);**
- **Os metais e ligas - CFC - (alumínio, cobre etc.) normalmente não fraturam por clivagem.**
- **Marcas de rios (River Marks) têm origem nas LD;**

QUASE-CLIVAGEM EM AÇO SAE 52100



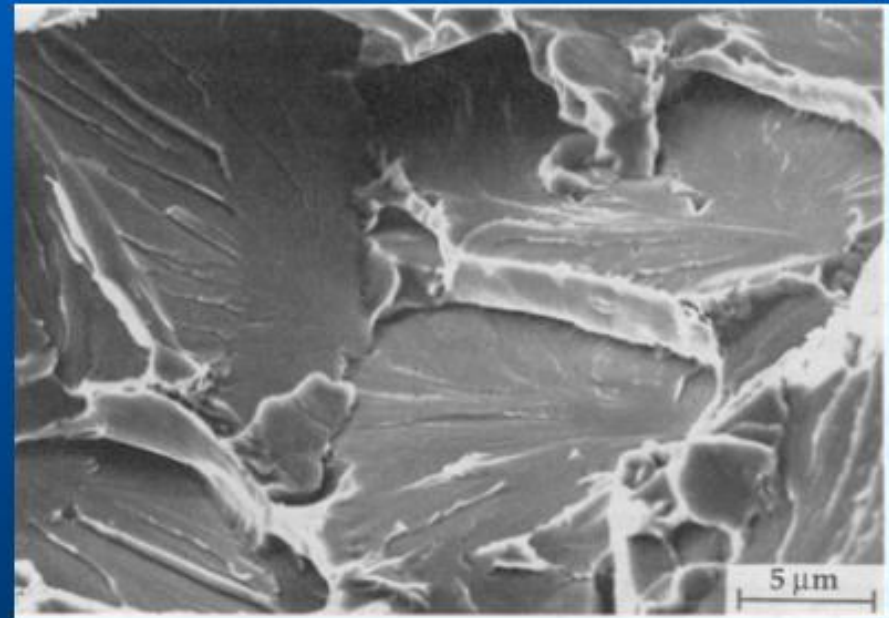
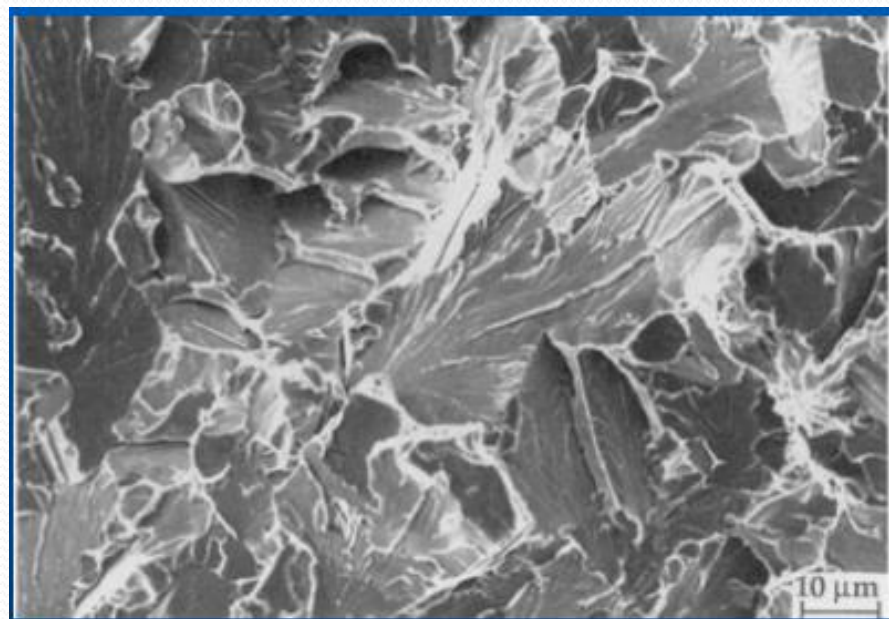
Mag = 540 X  
EHT = 20.00 kV

100µm  
┌──────────┐  
└──────────┘

Detector = SE1  
Date :10 Apr 2008

## CLIVAGEM/QUASE-CLIVAGEM

- QUASE-CLIVAGEM: AS MARCAS DE RIOS NÃO SÃO PARALELAS;
- COMBINAÇÃO DE CLIVAGEM COM DIMPLES, AGLOMERADOS DE ÁTOMOS-EX: AÇOS TEMPERADOS E REVENIDOS.



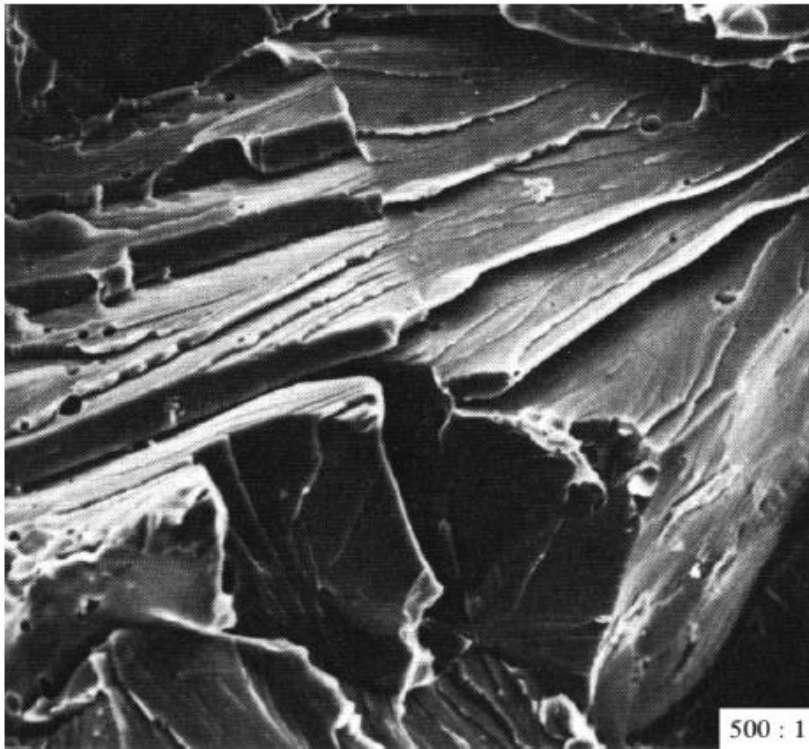


Fig. 7.12. – Degraus em  
facetas de clivagem

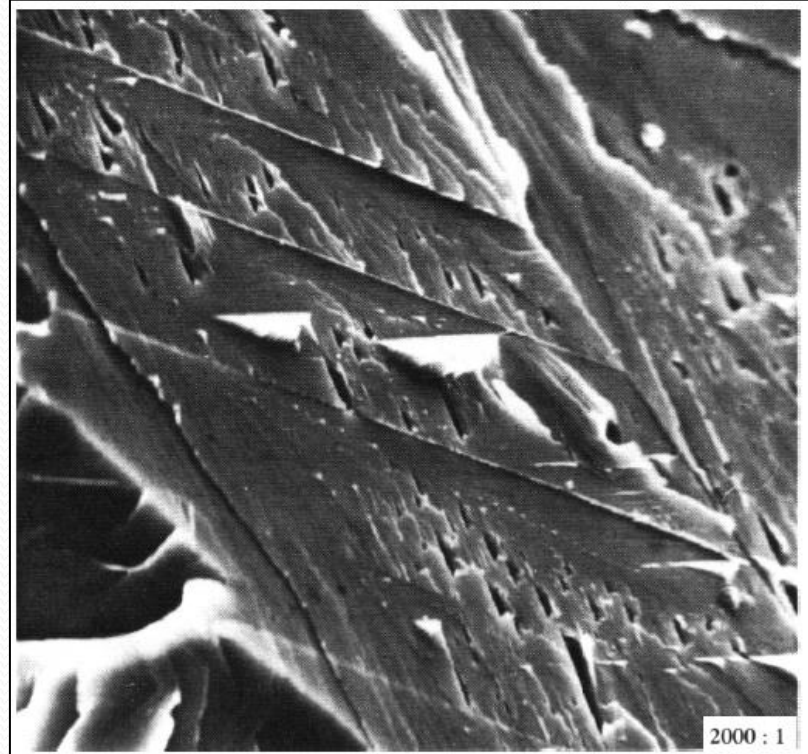
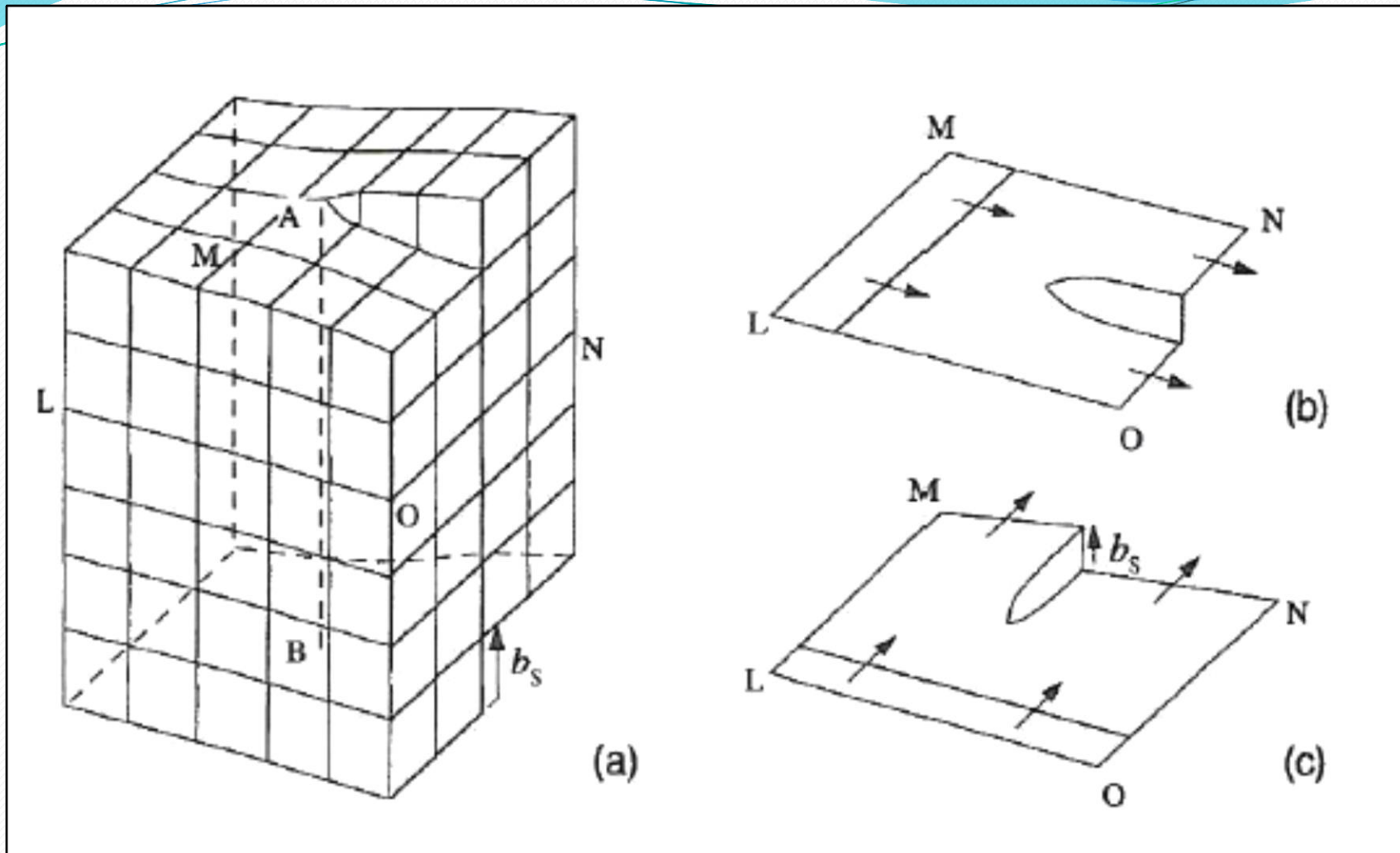


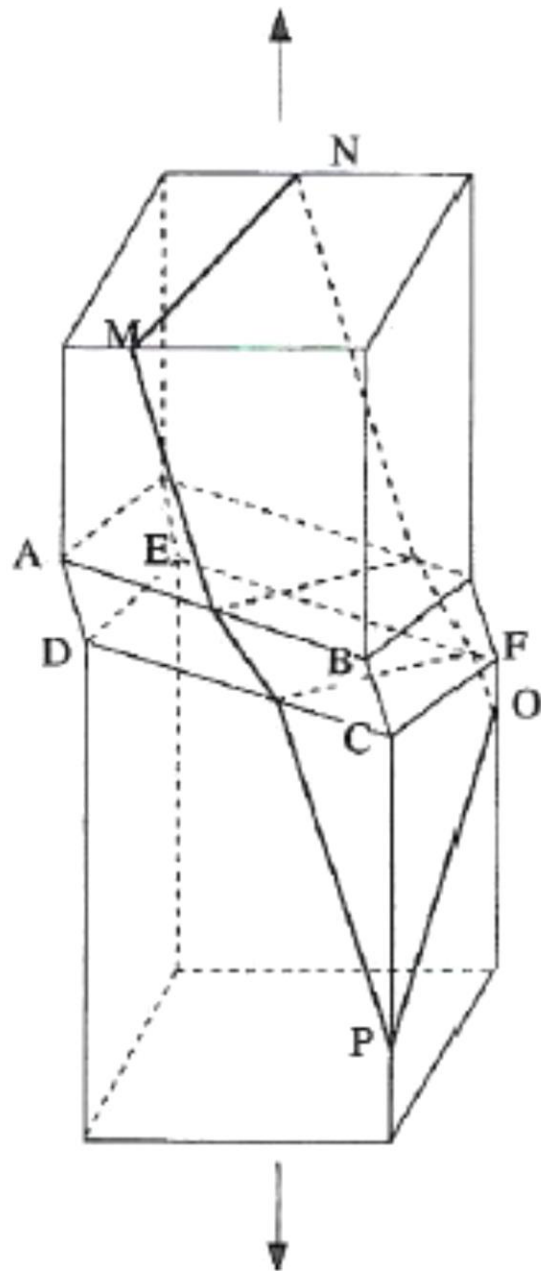
Fig. 7.14. – Linguas (tongues) em  
faceta de clivagem

**OS DEGRAUS SÃO FORMADOS POR FLORESTAS DE DISC. HÉLICE QUE MUDAM DE PLANO CRISTALINO, APROVEITANDO A ENERGIA DE DEFORMAÇÃO DA TRINCA.**



**FRATURA POR CLIVAGEM – FORMAÇÃO DO DEGRAU PELA PASSAGEM DA TRINCA POR LINHAS DE DISCORDÂNCIA EM HÉLICE**





## INFLUENCIA DA MACLAÇÃO DURANTE A FRATURA POR CLIVAGEM.

Com a sollicitação mecânica, a macla ABCD é formada. Com o alongamento do cristal, todos os planos rotacionam, exceto os planos paralelos ao plano da macla CDEF. A fratura por clivagem, MNOP, inclina nos contornos de macla

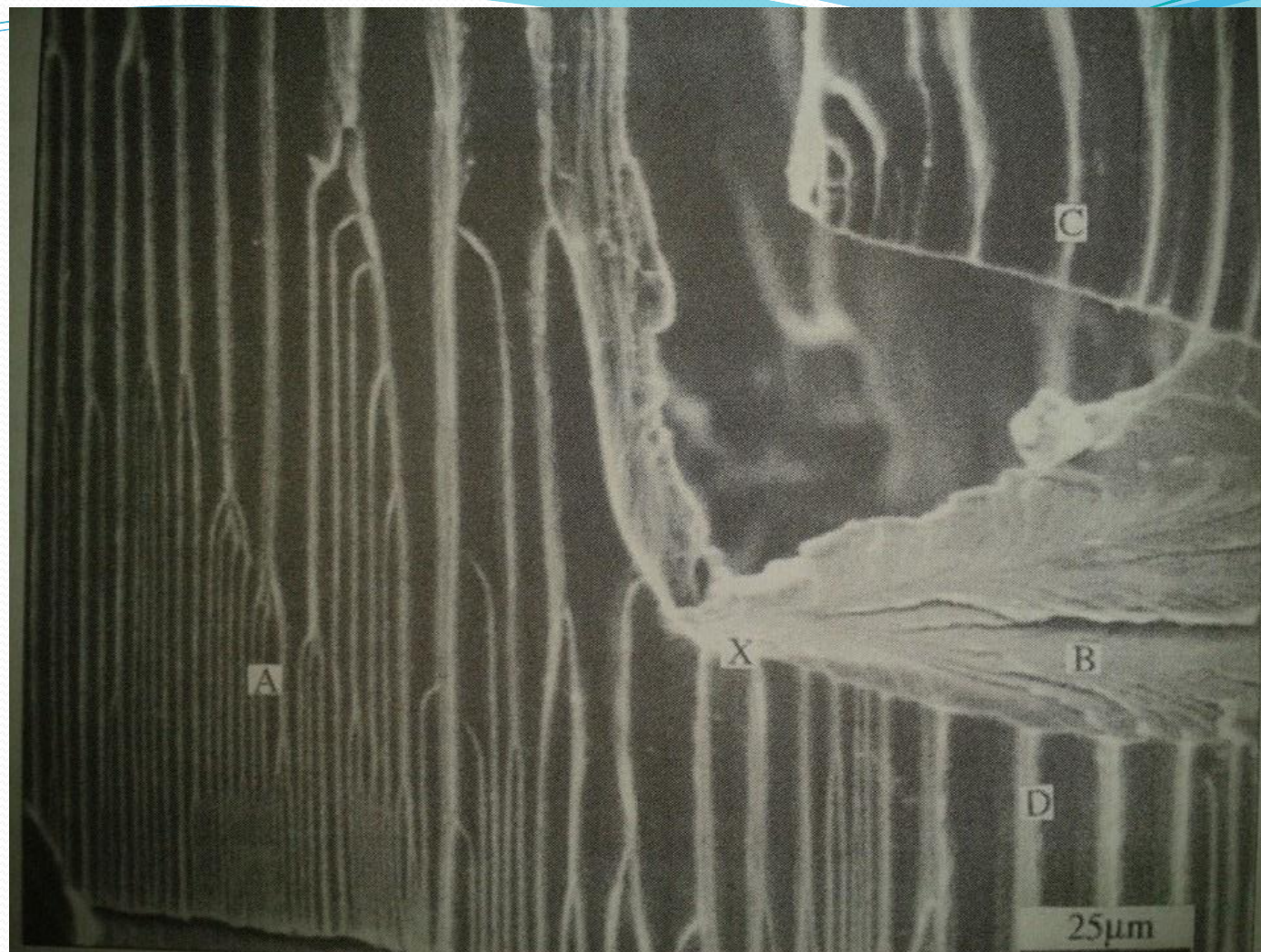


## FRATURA POR CLIVAGEM

**LÍNGUAS –  
MICROMACLAS ENTRE  
CONTORNO INCOERENTE  
DE MACLA E MATRIZ.  
OCORREM DEVIDO À  
ALTA VELOCIDADE DE  
PROPAGAÇÃO DA  
FRATURA (0,5 MACH).  
VEL.SOM AÇO: 5920 m/s**

*Tabela 2.2. Planos de clivagem e de cisalhamento de alguns materiais e estruturas cristalinas.*

<b>Estrutura Cristalina</b>	<b>Exemplo</b>	<b>Plano de Clivagem</b>	<b>Plano de cisalhamento primário</b>
CCC-cúbica de corpo centrado	Li, Na, K, Fe, a maioria dos aços, V, Cr, Mn, Cd, Mo, W, Ta.	{100}	{112}, {110},
CFC-cúbica de faces centradas	Cu, Ag, Au, Al, Ni, latão, aços inoxidáveis da série 300	Não sofrem clivagem	{111}
HCP-hexagonal compacta	Be, Mg, Zn, Sn, Ti, U, Cd, grafite	{1000}	{1122}, {1010}, {1000}



**FRATURA POR CLIVAGEM – TITÂNIO HC COM 0,38%O. OCORREU NA PRESENÇA DE MEIO CORROSIVO. PARTE A SÃO CAVIDADES DE CORROSÃO ALONGADAS (FLUTES)-DÚTIL. B-CLIVAGEM COM ORIGEM EM X. C E D JÁ EXISTIAM ANTES DE B.**

**TRINCA NUCLEADA NO CONTORNO DE MACLA MECÂNICA, FERRO PURO A  $-140\text{ }^{\circ}\text{C}$ , DEFORMADO EM TRAÇÃO.**



***Microcracks produced in iron by tensile deformation at 133 K.***

**ANÁLISE DE FALHAS**

**FRATURA FRÁGIL E DÚTIL**

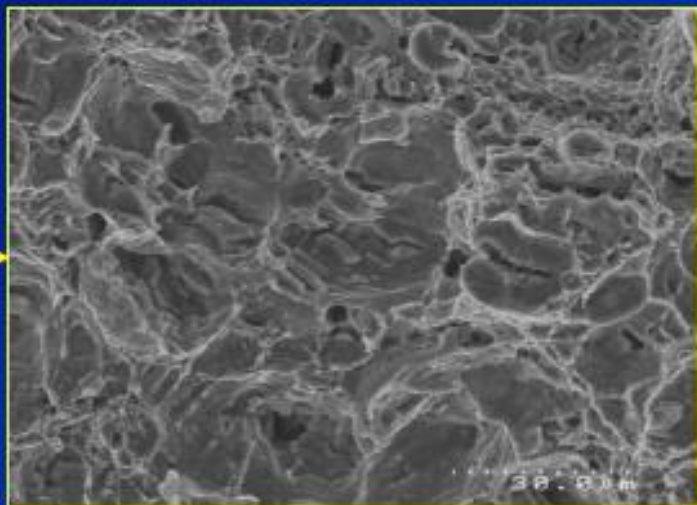
**FRATURA FRÁGIL X FRATURA DÚTIL**



**Ductile fracture**

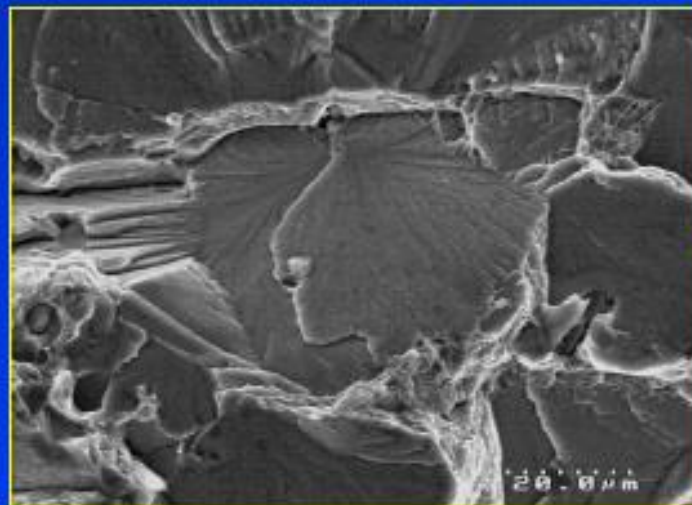


**Brittle fracture**



- **High energy** is absorbed by microvoid coalescence during ductile failure (high energy fracture mode)

**Less catastrophic**



- **Low energy** is absorbed during transgranular cleavage fracture (low energy fracture mode)

**More catastrophic**

**FRATURA FRÁGIL : POUCA OU  
NENHUMA DEFORMAÇÃO PLÁSTICA.**



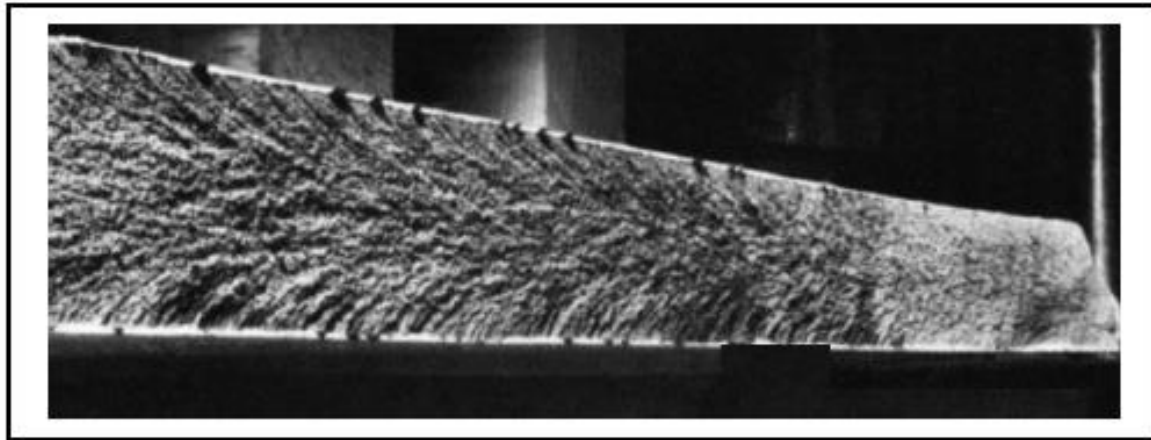


Fig.7.3. - Marcas de sargento. Origem da fratura à direita. <sup>(2a)</sup>

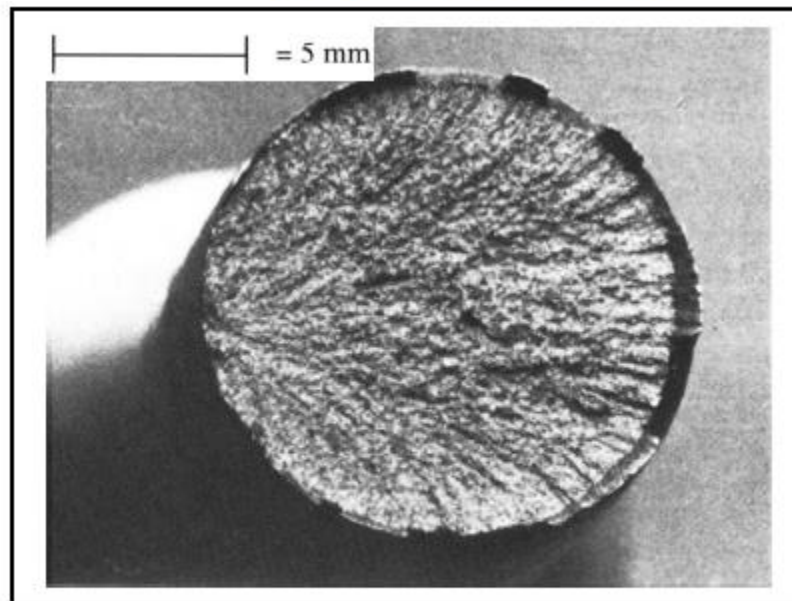
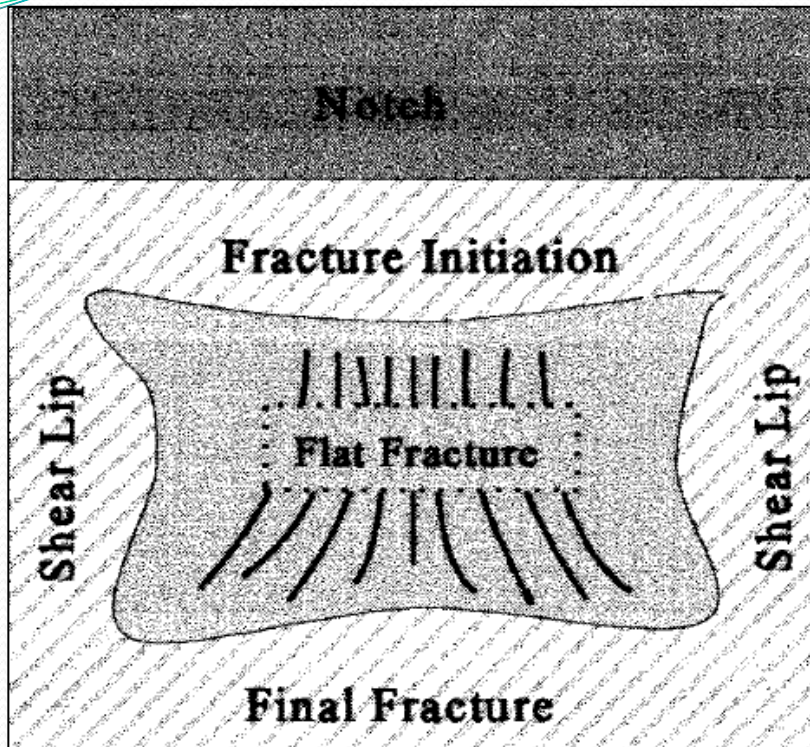


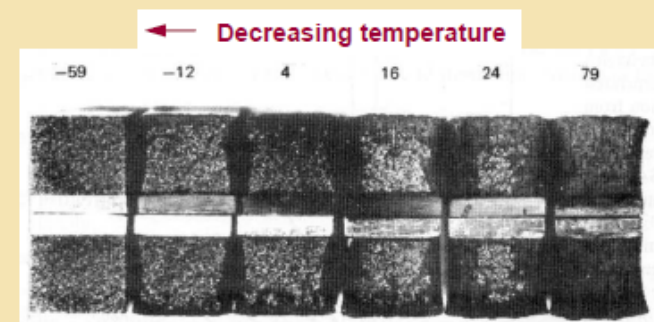
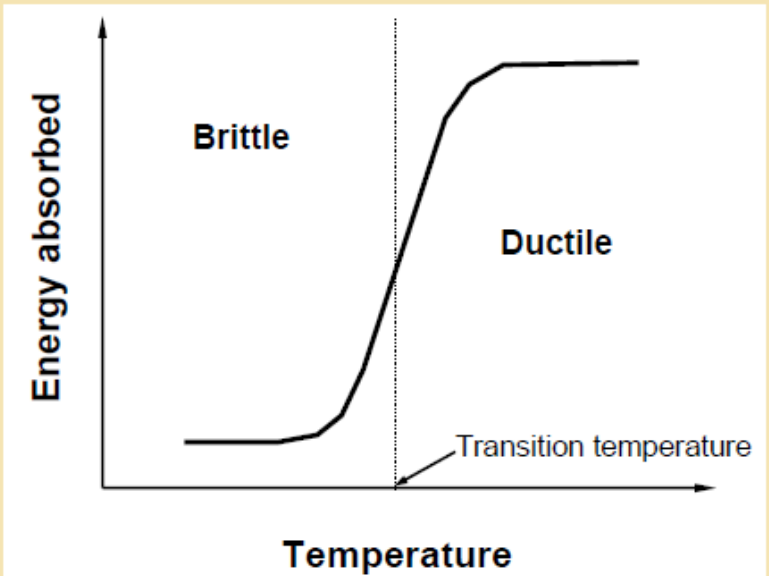
Fig. 7.5. – Marcas radiais e ausência de zona de cisalhamento <sup>(10)</sup>

**ENSAIOS PARA DETERMINAÇÃO DO  
COMPORTAMENTO FRÁGIL.**

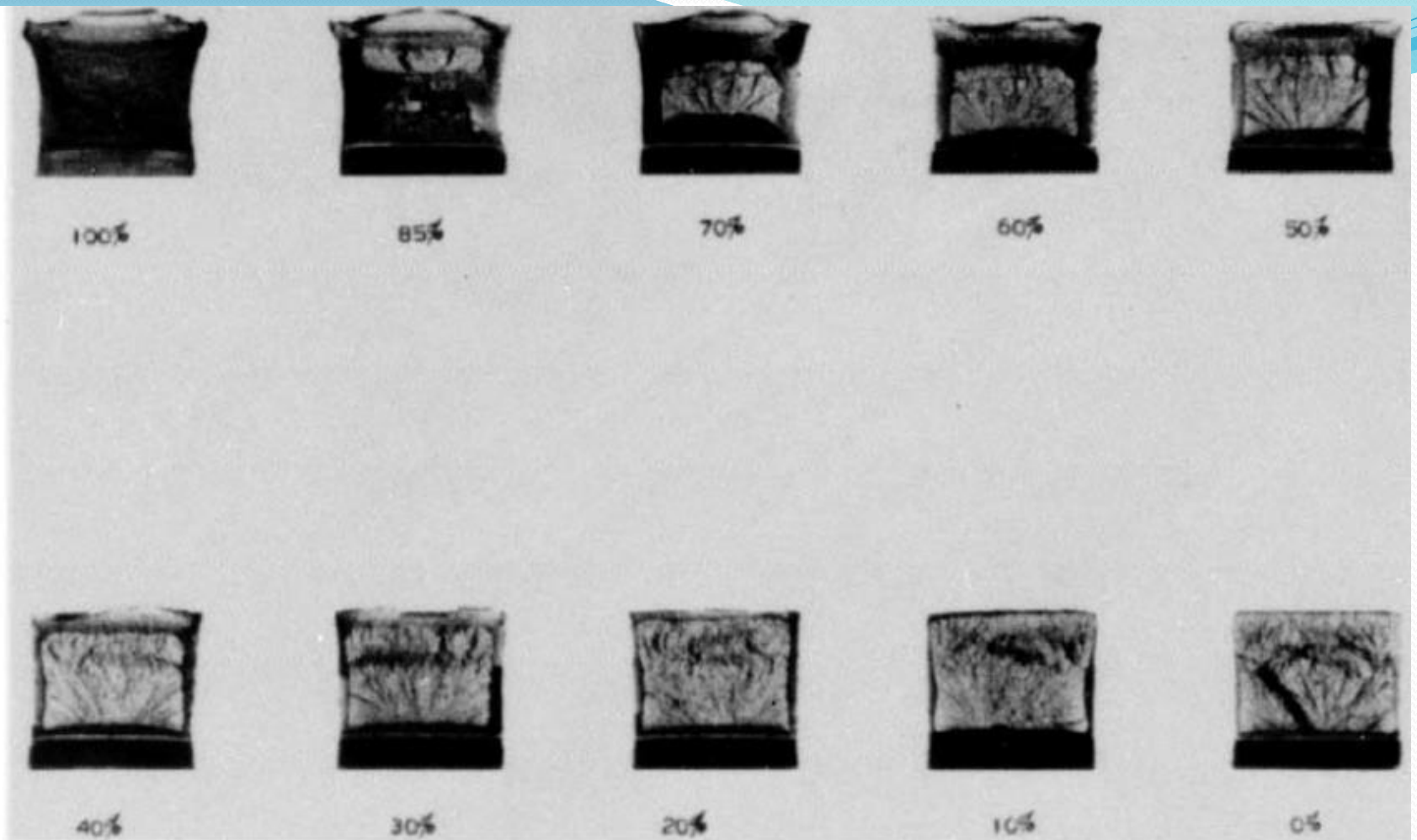
# ENSAIO DE IMPACTO - TEMPERATURA DE TRANSIÇÃO FRÁGIL-DÚTIL



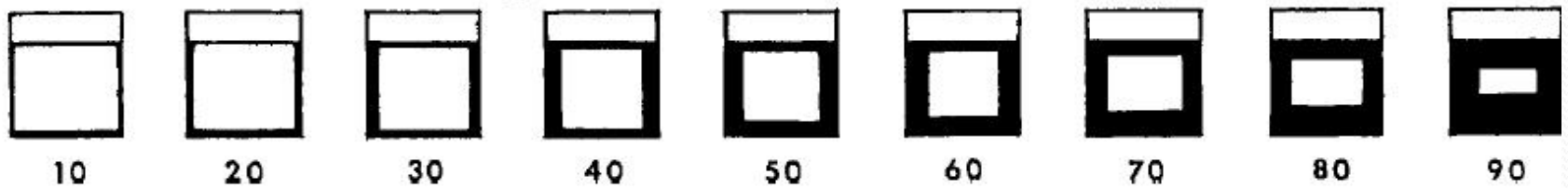
## Ductile-to-Brittle Transition



Fracture is more "brittle" with decreasing temperature

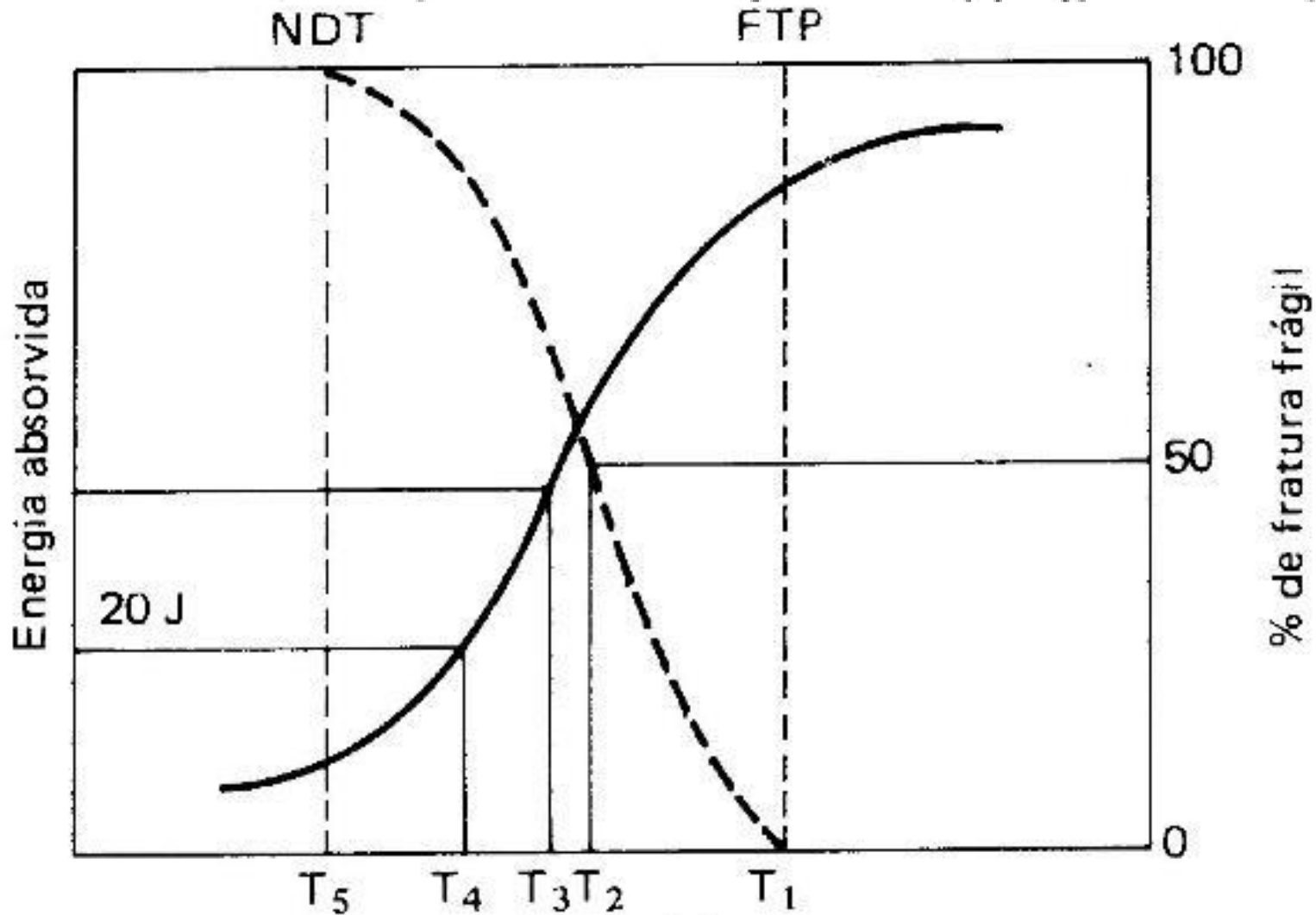


(a) Fracture Appearance Charts and Percent Shear Fracture Comparator



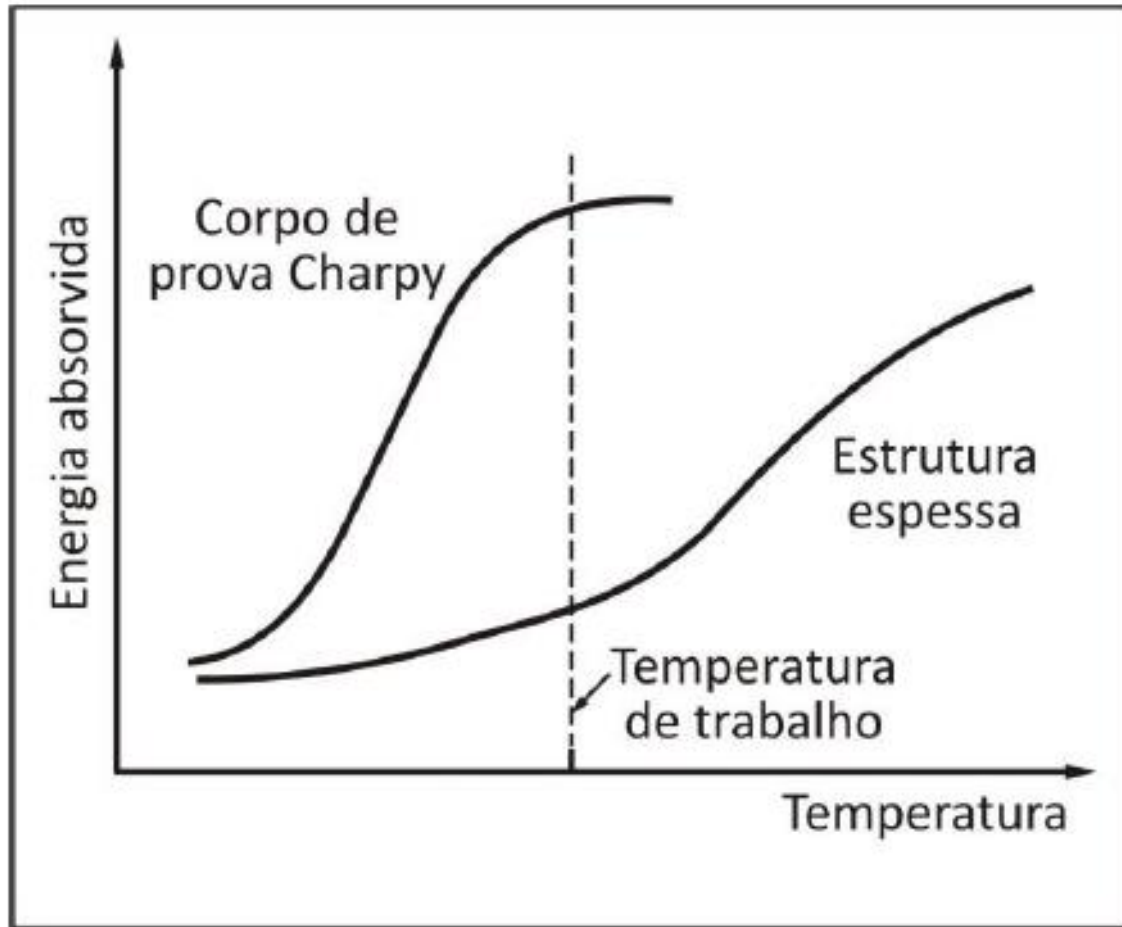
(b) Guide for Estimating Fracture Appearance

*nil ductility temperature*      *fracture transition plastic*



(a)

Se determinarmos a **temperatura de transição dúctil-frágil** de um aço que será utilizado para a fabricação de um casco de navio, por exemplo, com **corpos-de-prova Charpy** e a chapa efetivamente utilizada for de espessura maior, a curva de transição já não será a mesma.



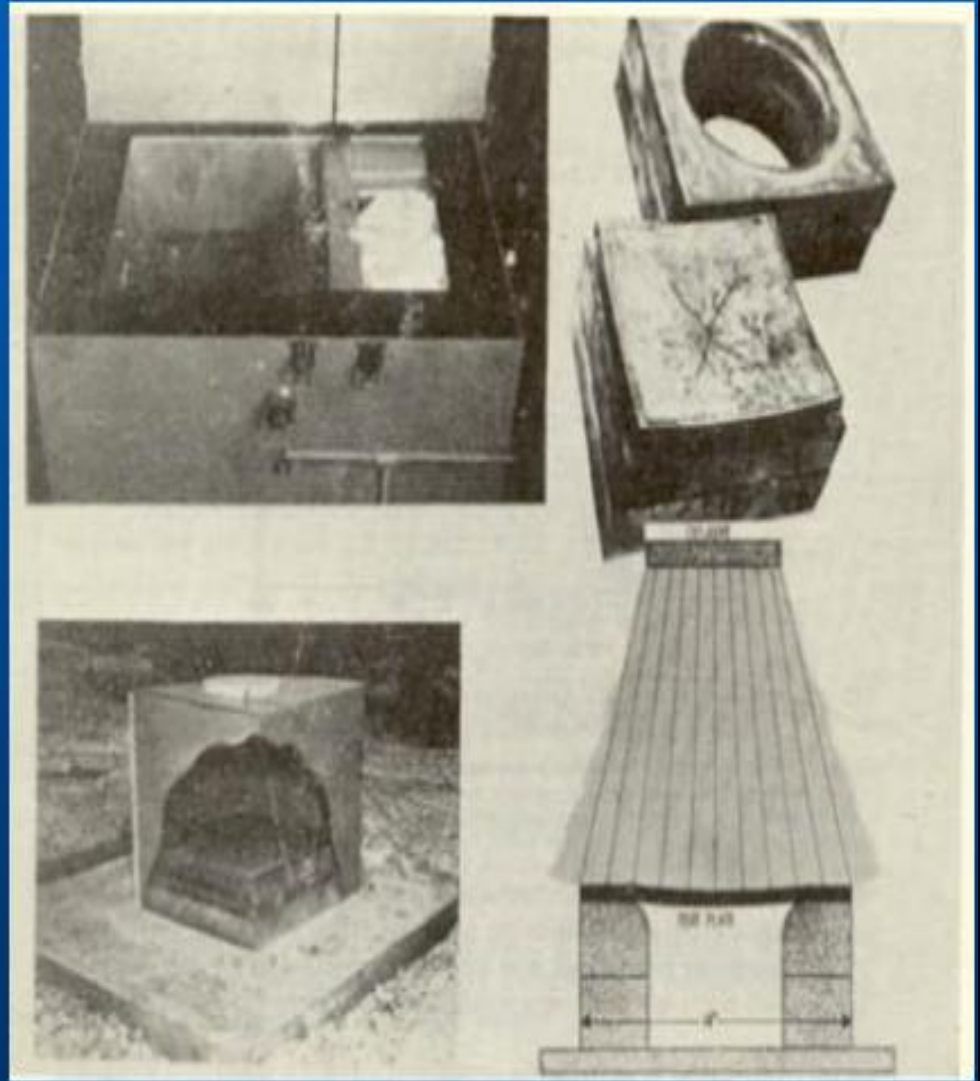
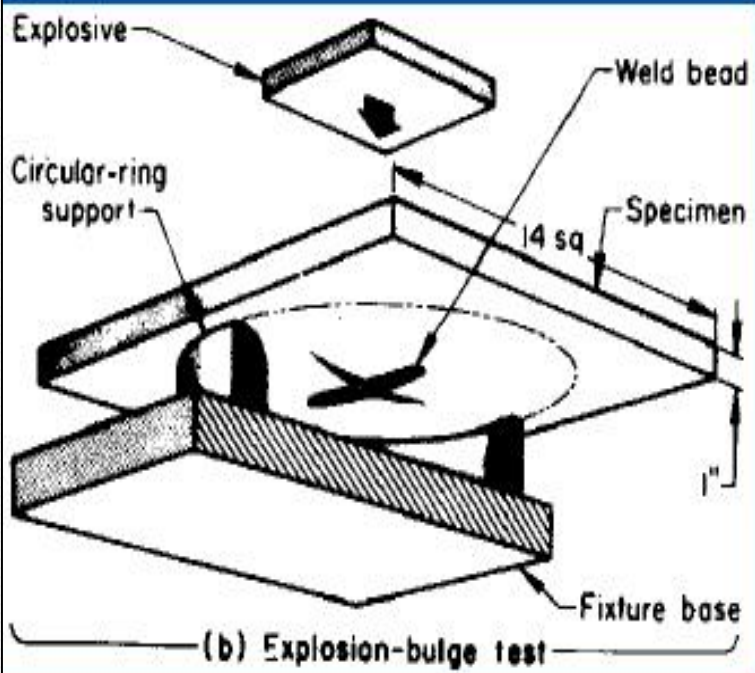
**Efeito da espessura em curvas de transição dúctil-frágil.**

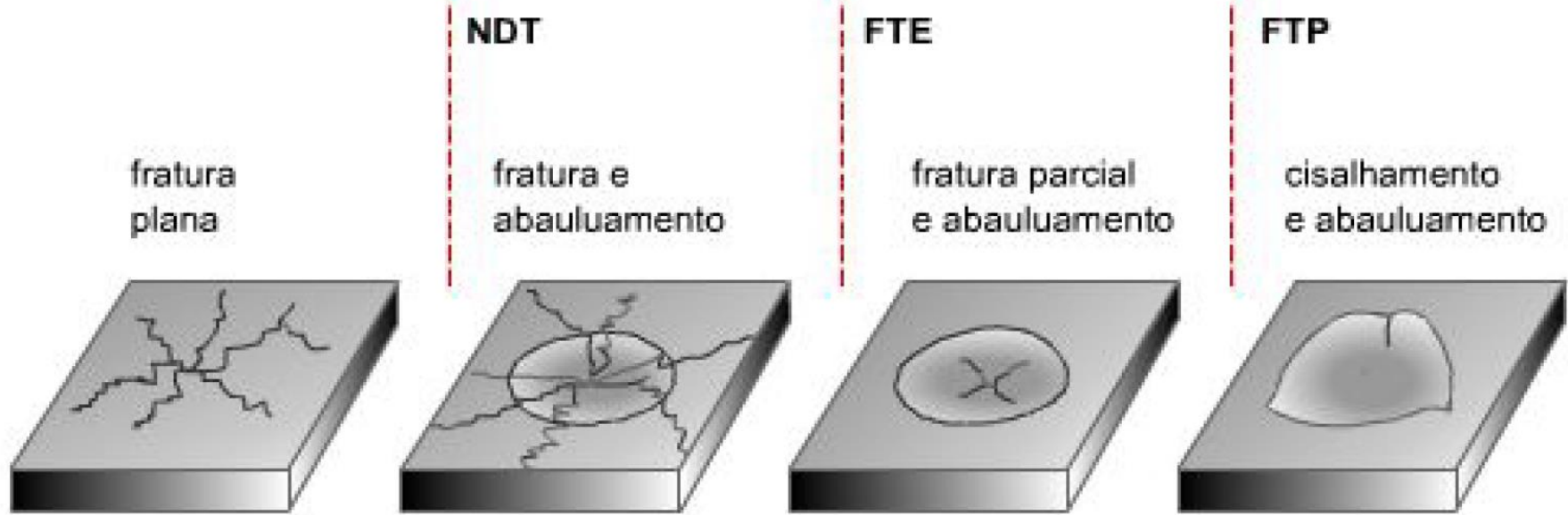
O primeiro teste desenvolvido foi o **teste de impacto por explosão** (*Explosion Bulge Test*); posteriormente foi desenvolvido o **teste de queda de peso** (*Drop Weight Test – DWT*).

## *Explosion Bulge Test*

- Utiliza corpo-de-prova com espessura real ou próxima;
- Cordão de solda com entalhe: fragilização;
- Uma carga explosiva é colocada acima do cp;
- A onda de choque leva o cp à fratura;
- Pode ser realizado em diferentes temperaturas;
- Boa correlação com ensaio de impacto Charpy.





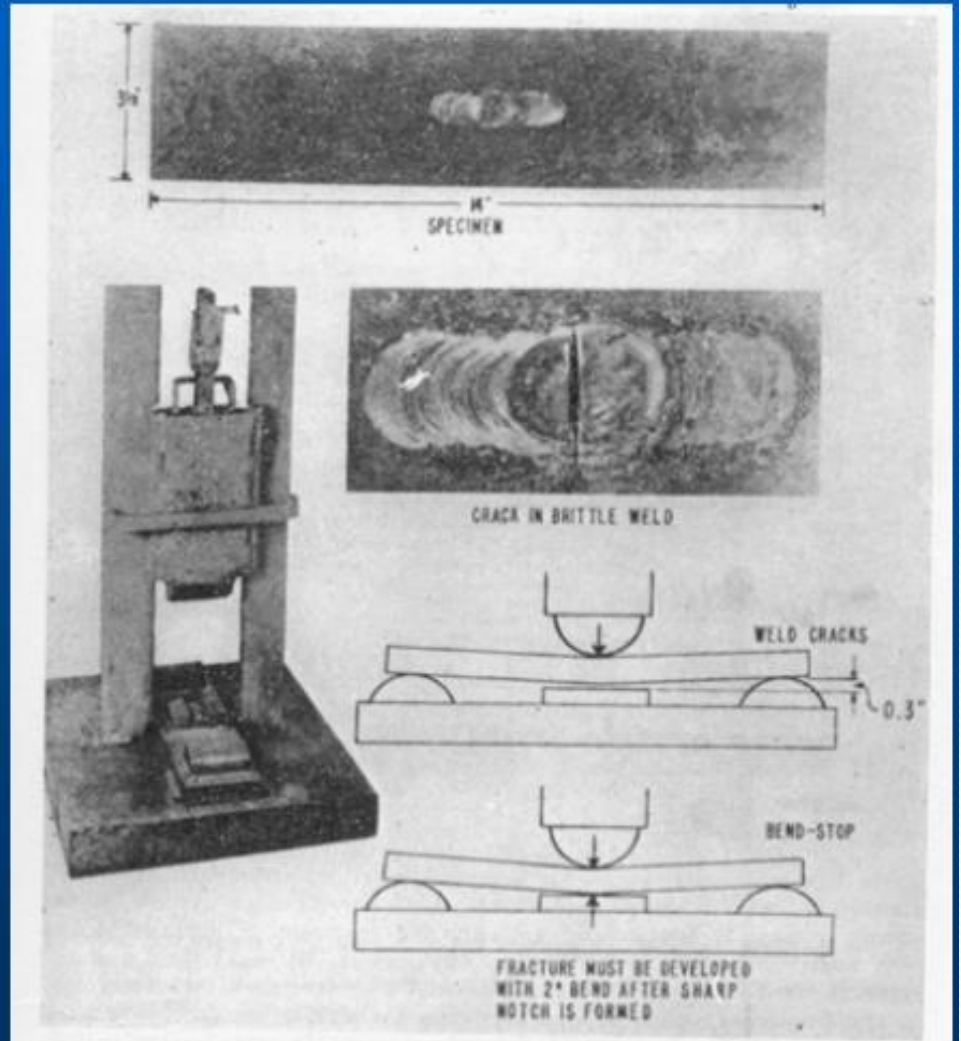
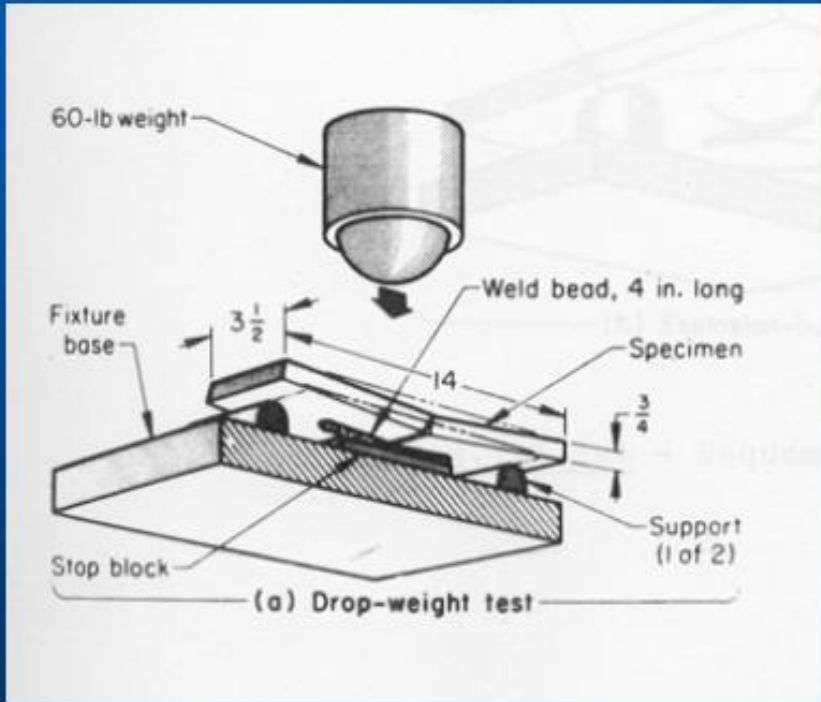


Aspecto da fratura em função da temperatura para o teste de explosão com iniciador de trinca

- **NDT-Nihil Ductility Temperature;**
- **FTE -Fracture Transition Elastic;**
- **FTP-Transition Fracture Plastic.**

## *Drop Weight Test (DWT)*

- Utiliza corpo-de-prova retangular com cordão de solda entalhado: fragilização;
- Carga de impacto por queda livre de uma massa padronizada: 60 libras a 10 ft de altura ;
- A flexão do cp é limitada a 5° (batente);
- Pode ser realizado em diferentes temperaturas;
- Norma ASTM E 208.



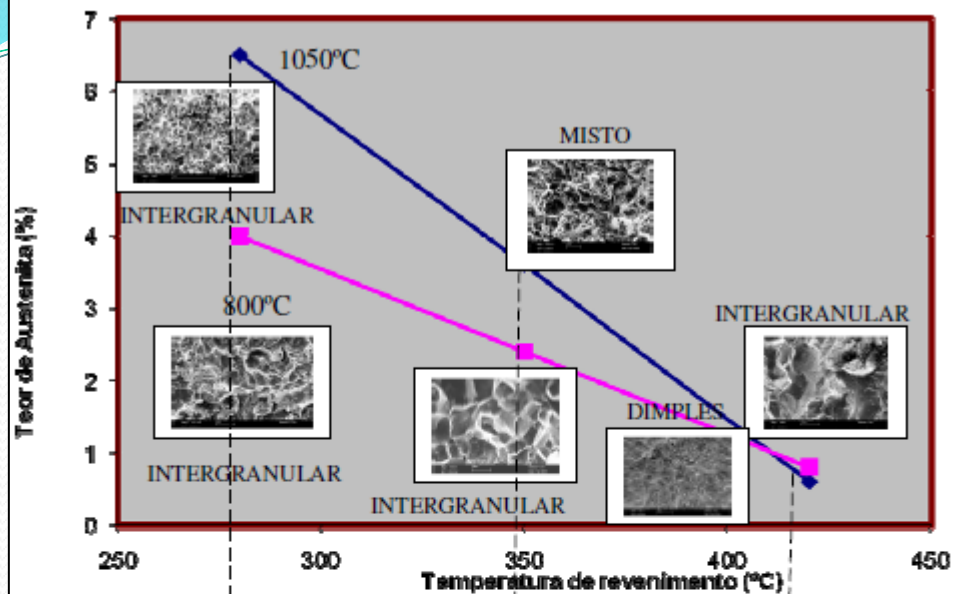
**ANÁLISE DE FALHAS**

**FRATURA FRÁGIL E DÚTIL**

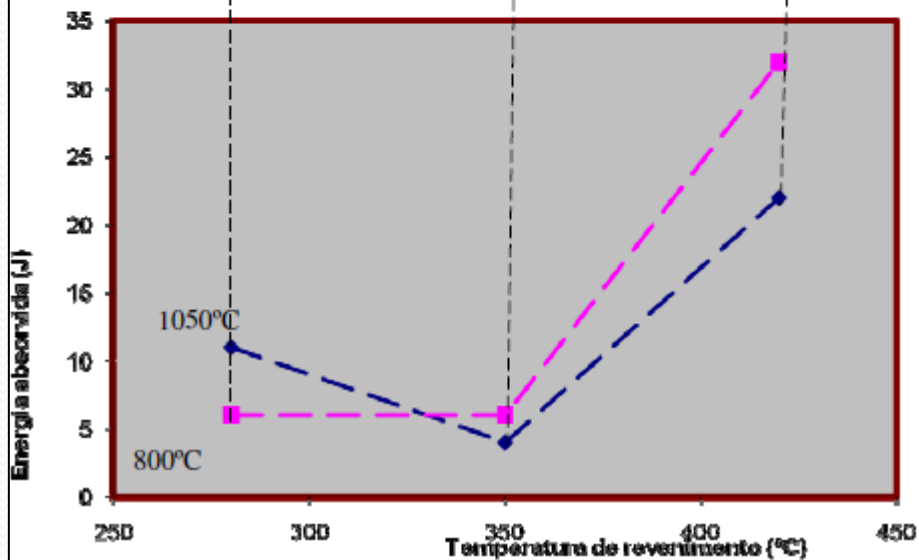
**ESTUDOS DE CASOS**

# CASO I – FRAGILIZAÇÃO DA MARTENSITA REVENIDA

Austenita retida X T Revenimento



E Absorvida X T Revenimento



**PRECIPITAÇÃO DE FILMES DE CEMENTITA INTER E INTRA-RIPAS DE MARTENSITA**

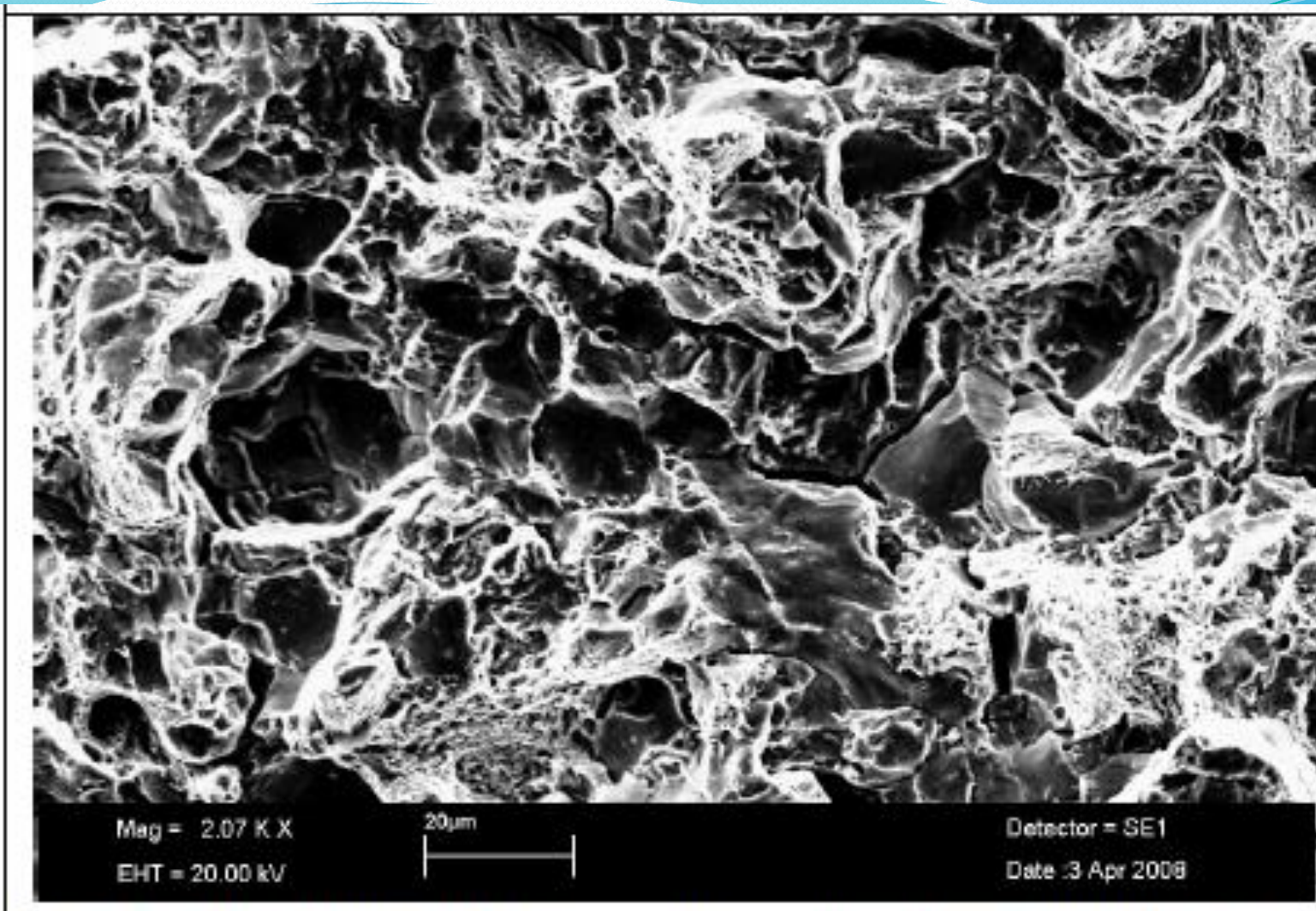


Figura 4.33 – Superfície de fratura do corpo-de-prova de impacto C3, austenitizado em 1050°C, temperado em óleo a 80°C e revenido em 350°C. Fratura por “dimples” e intergranular.

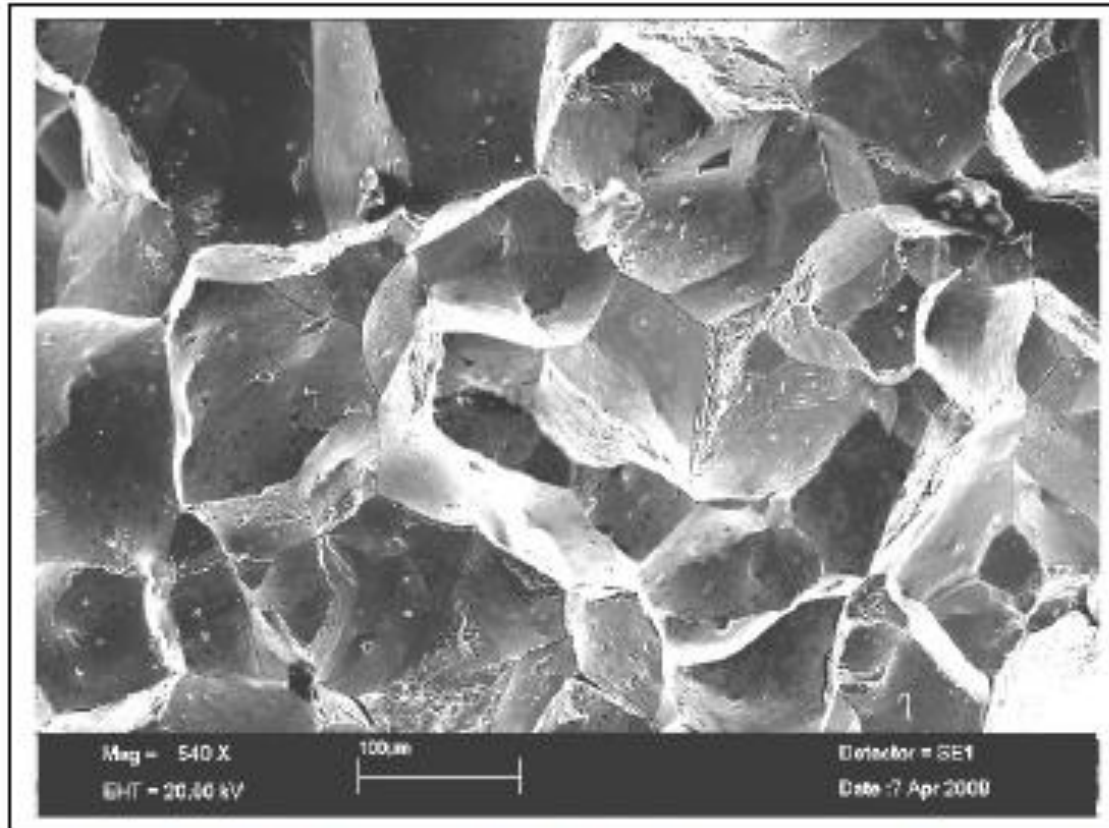
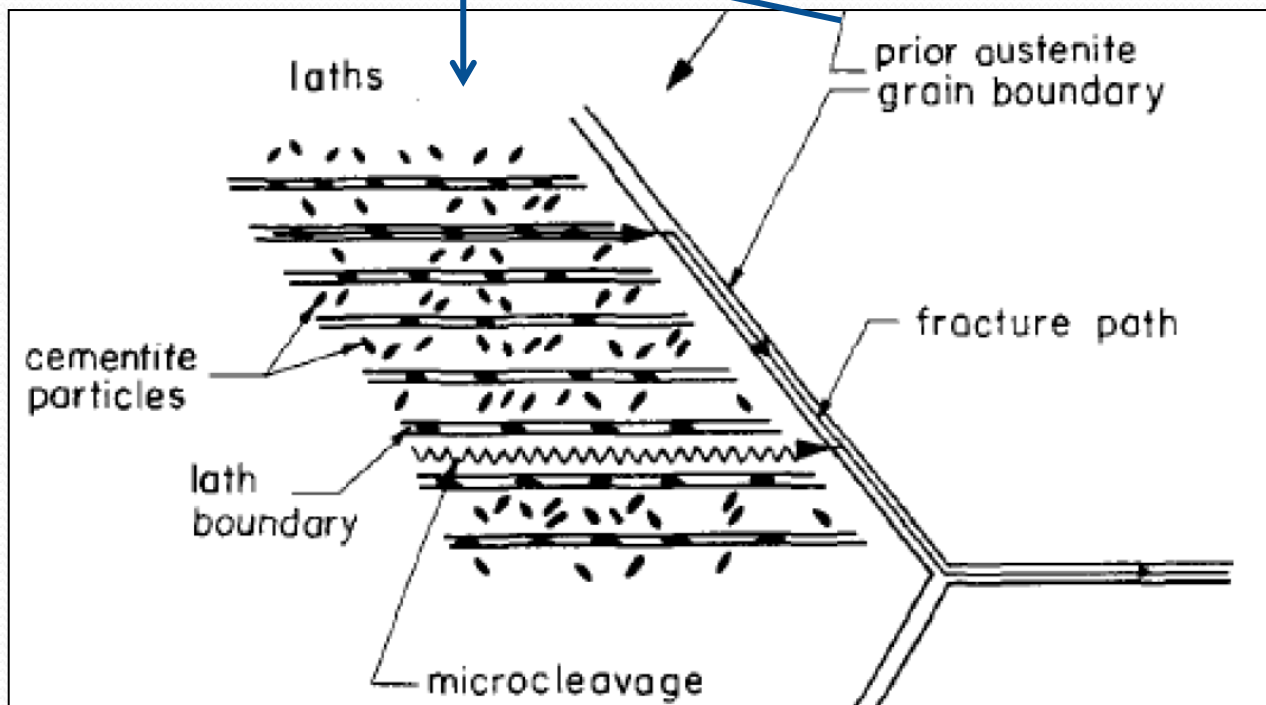
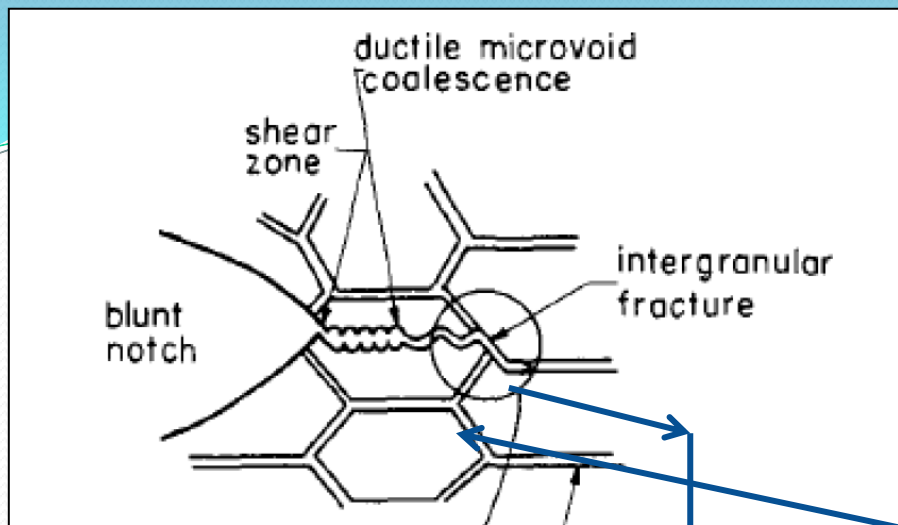


Figura 4.42 – Superfície de fratura do corpo-de-prova C6, austenitizado em 800°C, temperado em óleo a 80°C e revenido em 350°C. Micromecanismo intergranular.





Esquema do micromecanismo de fratura misto para a FMR (LEE et al 1989)

## CASO III – TORRE COM CHAPA CLADEADA

- FORNECIDO TORRE COM CHAPA DE AÇO ASME AS 516 – GR 70 COM CLAD DE AISI 304L ;
- CHAPA CLADEADA POR EXPLOSÃO;
- SUBMETIDO AO ENSAIO DE CORROSÃO INTERCRISTALINA-ASTM A 262 – PRÁTICA E – SENSITIZAÇÃO EM 600°C -1HORA – MÍNIMO DE 15 HORA EM  $\text{CuSO}_4 + \text{H}_2\text{SO}_4 - 16\%$  - DOBRAMENTO - FRATUROU;
- NORMA AFIRMA QUE NÃO PODE HAVER FRATURA INTERCRISTALINA.



Designation: A 262 – 02a<sup>ε1</sup>

## Standard Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels<sup>1</sup>

This standard is issued under the fixed designation A 262; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## PRACTICE A—OXALIC ACID ETCH TEST FOR CLASSIFICATION OF ETCH STRUCTURES OF AUSTENITIC STAINLESS STEELS 2

A 262 – 02a<sup>41</sup>

sensitization, it may be difficult to reveal the presence of step structures by electrolytic etching with oxalic acid. In such cases, an electrolyte of a 10 % solution of ammonium persulfate, (NH<sub>4</sub>)<sub>2</sub>S<sub>2</sub>O<sub>8</sub>, may be used in place of oxalic acid. An etch of 5 or 10 min at 1 A/cm<sup>2</sup> in a solution at room temperature readily develops step structures on such specimens.

## 6. Classification of Etch Structures

6.1 The etched surface is examined on a metallurgical microscope at 250× to 500× for wrought steels and at about 250× for cast steels.

6.2 The etched cross-sectional areas should be thoroughly examined by complete traverse from inside to outside diameters of rods and tubes, from face to face on plates, and across all zones such as weld metal, weld-affected zones, and base plates on specimens containing welds.

6.3 The etch structures are classified into the following types (Note 2):

6.3.1 *Step Structure* (Fig. 1)—Steps only between grains, no ditches at grain boundaries.

6.3.2 *Dual Structure* (Fig. 2)—Some ditches at grain boundaries in addition to steps, but no single grain completely surrounded by ditches.

6.3.3 *Ditch Structure* (Fig. 3)—One or more grains completely surrounded by ditches.

6.3.4 *Isolated Ferrite* (Fig. 4)—Observed in castings and welds. Steps between austenite matrix and ferrite pools.

6.3.5 *Interdendritic Ditches* (Fig. 5)—Observed in castings and welds. Deep interconnected ditches.

6.3.6 *End-Grain Pitting I* (Fig. 6)—Structure contains a few deep end-grain pits along with some shallow etch pits at 500×. (Of importance only when nitric acid test is used.)

6.3.7 *End-Grain Pitting II* (Fig. 7)—Structure contains numerous, deep end-grain pits at 500×. (Of importance only when nitric acid test is used.)



FIG. 1 Step Structure (500×) (Steps between grains, no ditches at grain boundaries)

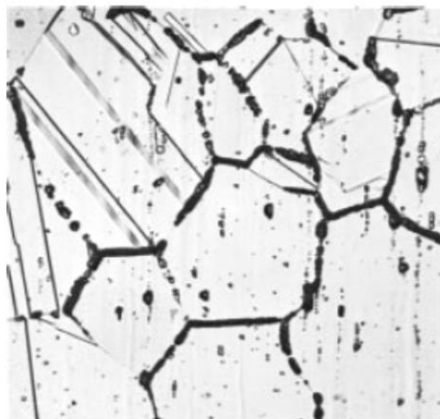


FIG. 2 Dual Structure (250×) (Some ditches at grain boundaries in addition to steps, but no one grain completely surrounded)

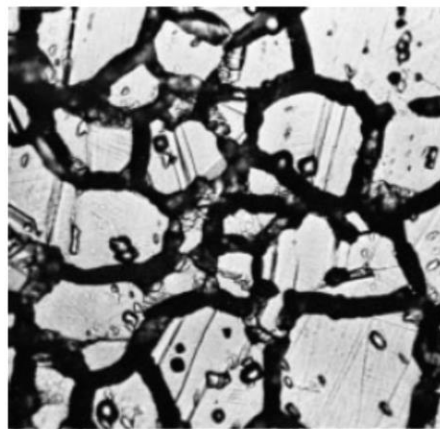


FIG. 3 Ditch Structure (500×) (One or more grains completely surrounded by ditches)

NOTE 2—All photomicrographs were made with specimens that were etched under standard conditions: 10 % oxalic acid, room temperature, 1.5 min at 1 A/cm<sup>2</sup>.

6.4 The evaluation of etch structures containing steps only and of those showing grains completely surrounded by ditches in every field can be carried out relatively rapidly. In cases that appear to be dual structures, more extensive examination is required to determine if there are any grains completely encircled. If an encircled grain is found, the steel should be evaluated as a ditch structure. Areas near surfaces should be examined for evidence of surface carburization.

A 262 – 02a<sup>41</sup>

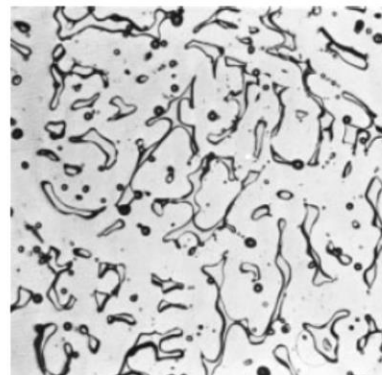


FIG. 4 Isolated Ferrite Pools (250×) (Observed in castings and welds. Steps between austenite matrix and ferrite pools)

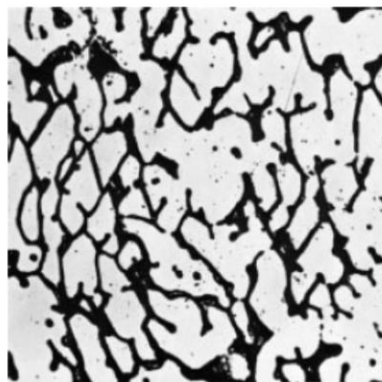


FIG. 5 Interdendritic Ditches (250×) (Observed in castings and welds. Deep interconnected ditches)

6.4.1 On stainless steel castings (also on weld metal), the steps between grains formed by electrolytic oxalic acid etching tend to be less prominent than those on wrought materials or are entirely absent. However, any susceptibility to intergranular

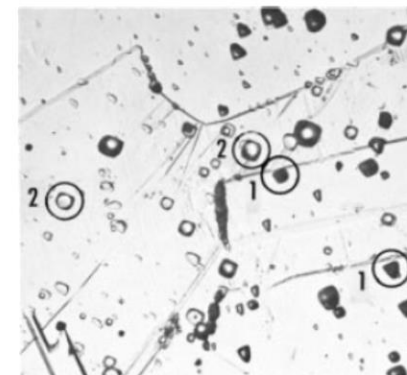


FIG. 6 End Grain Pitting I (500×) (A few deep end grain pits (see 1 in figure) and shallow etch pits (2))

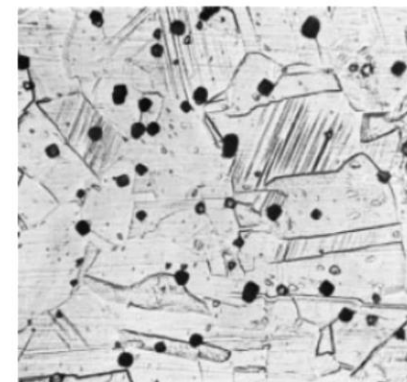


FIG. 7 End Grain Pitting II (500×)

This or a greater concentration of end grain pits at 500× (using standard etching conditions) indicates that the specimen must be tested when screening is for nitric acid test.

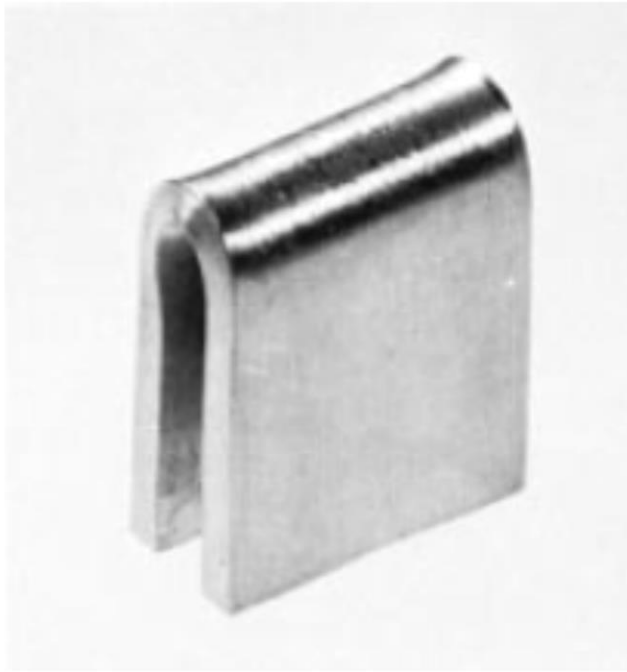
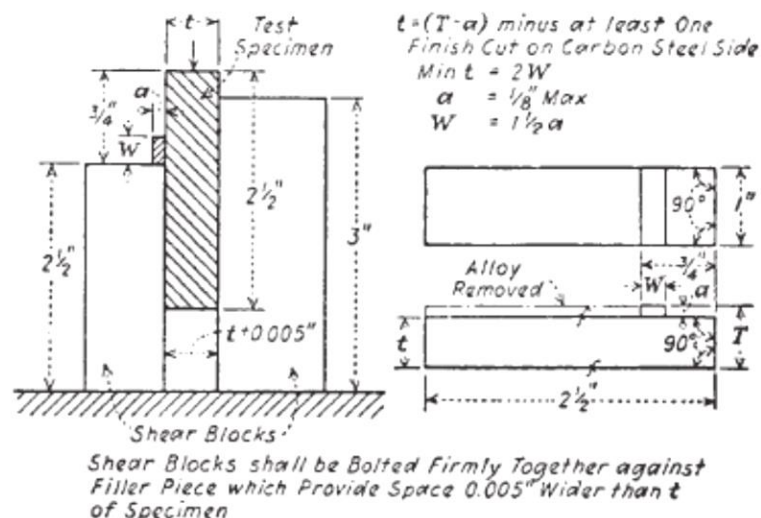


FIG. 10 A Bent Copper–Copper Sulfate–Sulfuric Acid Test Specimen

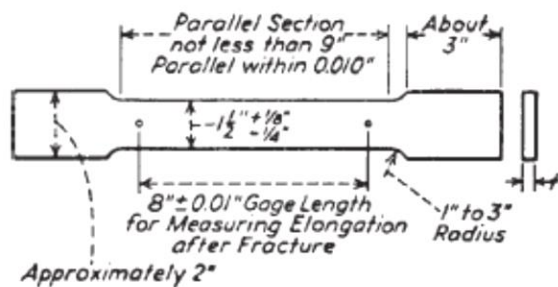
**PRÁTICA E- A AMOSTRA FICA EM UMA SOLUÇÃO DE SULFATO DE COBRE COM ÁCIDO SULFÚRICO 16% DURANTE 15 HORAS NO MÍNIMO E DEPOIS É FEITO O DOBRAMENTO.**



## Metric Equivalents

in.	mm	in.	mm
0.005	0.127	1	25.4
1/8	3.18	2 1/2	64.5
3/4	19.1	3	76.2

FIG. 1 Test Specimen and Method of Making Shear Test of Clad Plate



## Metric Equivalents

## 9. Test Specimens

9.1 The tension test specimens from plate shall conform to the requirements prescribed in the specifications for the base metal.

9.2 Bend test specimens for the alternative bond strength tests, shall be taken at right angles to its longitudinal axis.

9.3 When required by the purchaser, the shear test specimen should be taken near a top or bottom corner of the plate as rolled, parallel to its longitudinal axis, or other location that is representative of the final product.

9.4 For plates 1 1/2 in. [38 mm] and under in thickness, tension test specimens shall be the full thickness of the material, except as specified in 8.1 and 8.2.

9.5 For plates over 1 1/2 in. [38 mm] in thickness, tension tests shall be of the form shown in Fig. 3 and shall be of all base steel conforming to the requirements of the specification for the base steel.

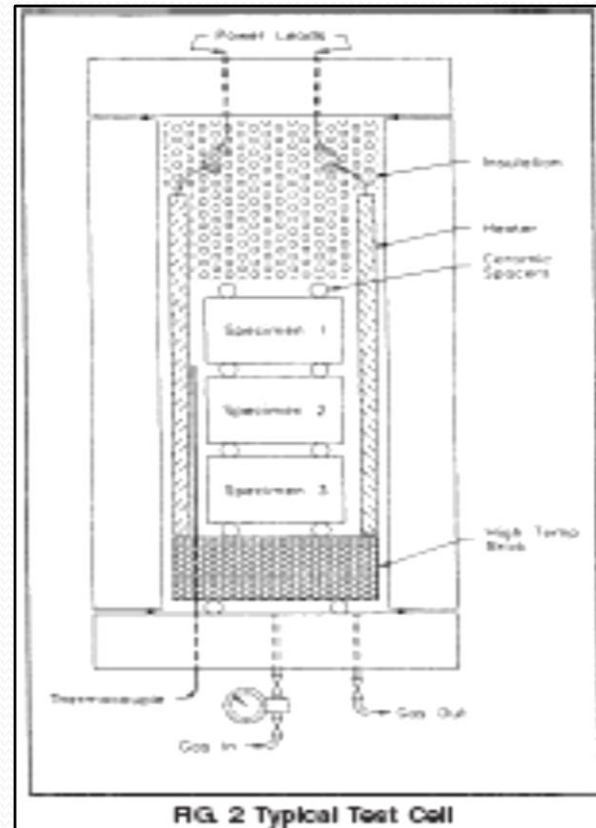
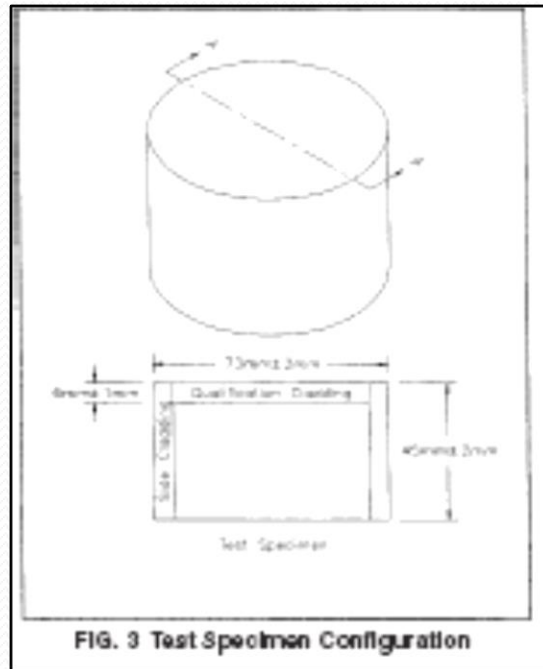
9.6 The bend test specimen used for bond strength determination shall be 1 1/2 in. wide [38 mm] by not more than 3/4 in. [19 mm] in thickness and shall be machined to the form and dimensions shown in Fig. 2, or may be machined with both edges parallel. In reducing the thickness of the specimen, both the alloy cladding and the base steel shall be machined so as to maintain the same ratio of clad metal to base steel as is maintained in the plate, except that the thickness of the clad metal need not be reduced below 1/8 in. [3.1 mm]. The sides of the bend test specimen used for bond strength determination may have the corners rounded to a radius not over 1/16 in. [1.6 mm] for plates, 2 in. [50 mm] and under in thickness, and not over 1/8 in. [3.1 mm] for plates over 2 in. [50 mm] in thickness.



Designation: G 146 – 01 (Reapproved 2007)

## Standard Practice for Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service<sup>1</sup>

This standard is issued under the fixed designation G 146; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last approval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or approval.

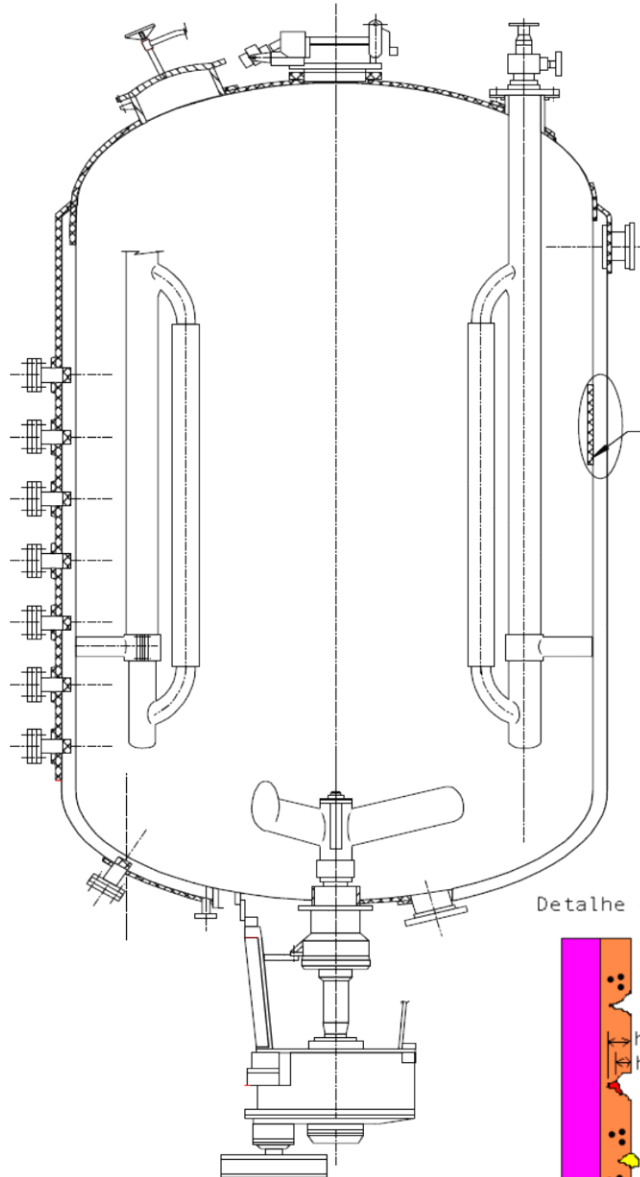


TORRE DE REFINARIA PETROQUÍMICA



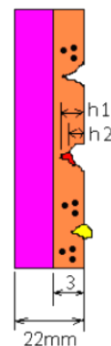


# CASO III – TORRE COM CHAPA CLADEADA








Ver detalhe do clad abaixo.

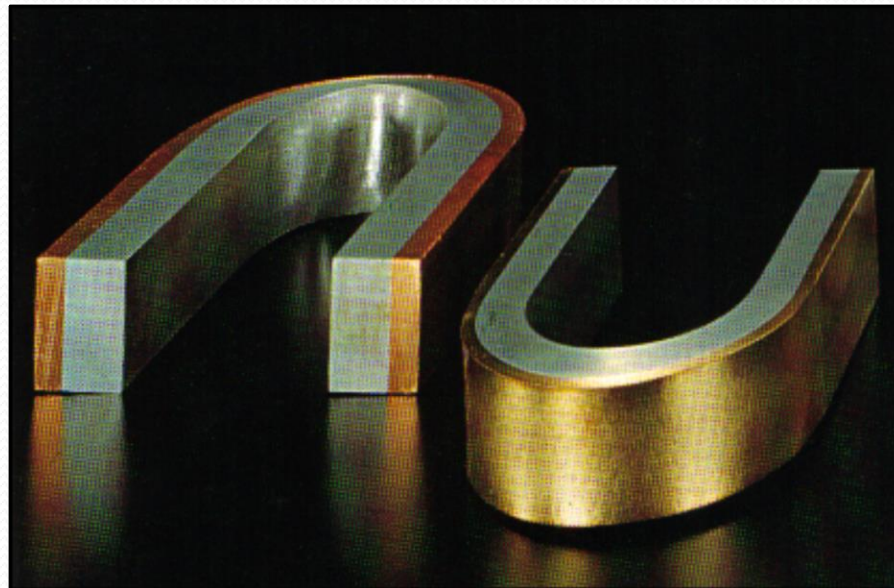
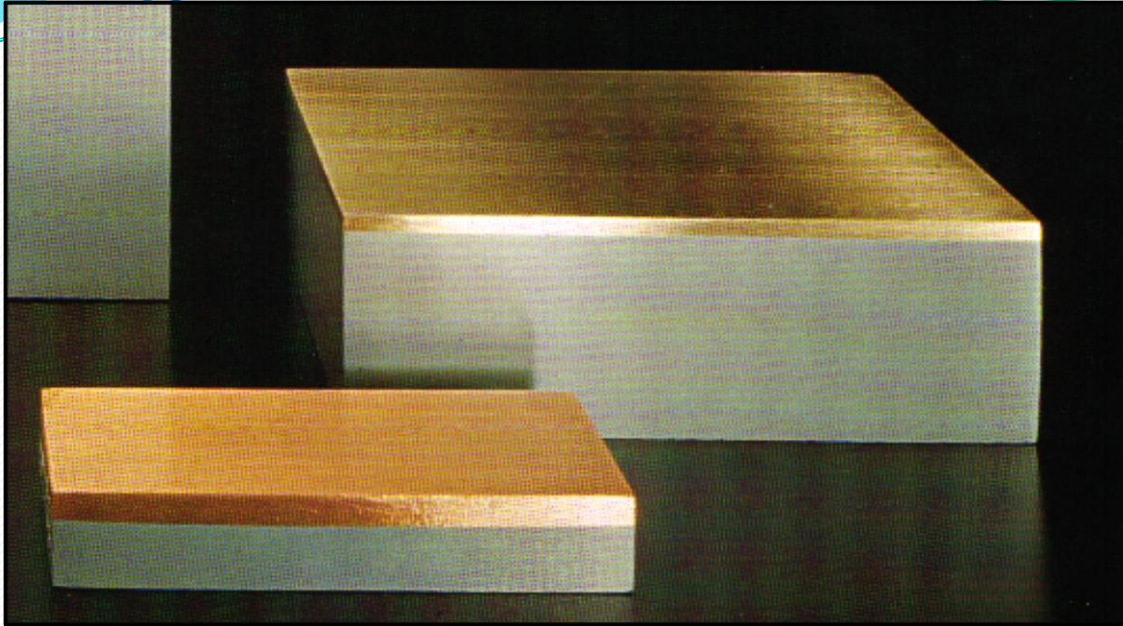
Detalhe do Clad no Reator para Polimerizacao



## Legenda

-  Incrustação na Superfície do Clad
-  Substrato, Aço Carbono  
ASTMA 516 Gr. 70
-  Clad, Aço Inox 304L
-  Incrustação no fundo do pite  
 $h_1 > h_2$
-  Superfície Rugosa

# CHAPA CLADEADA



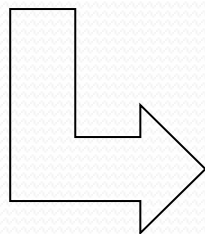
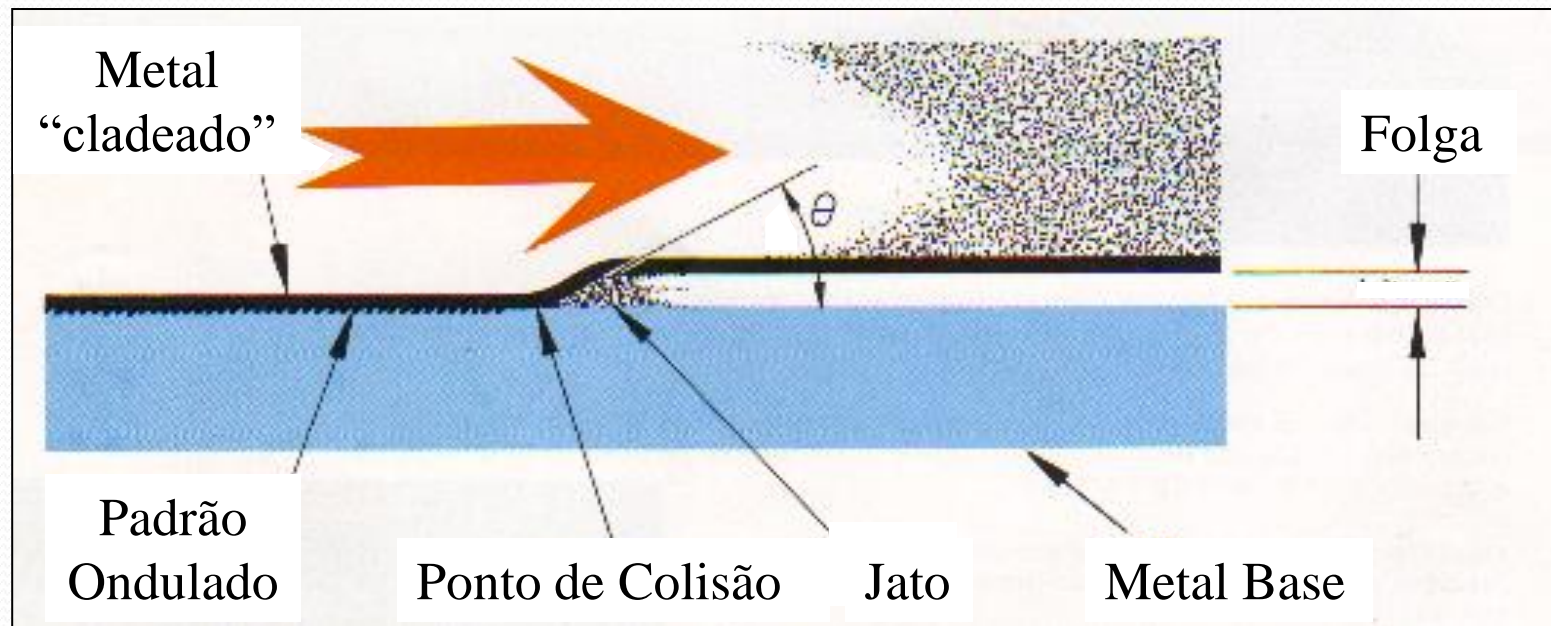
# CASO III – TORRE COM CHAPA CLADEADA



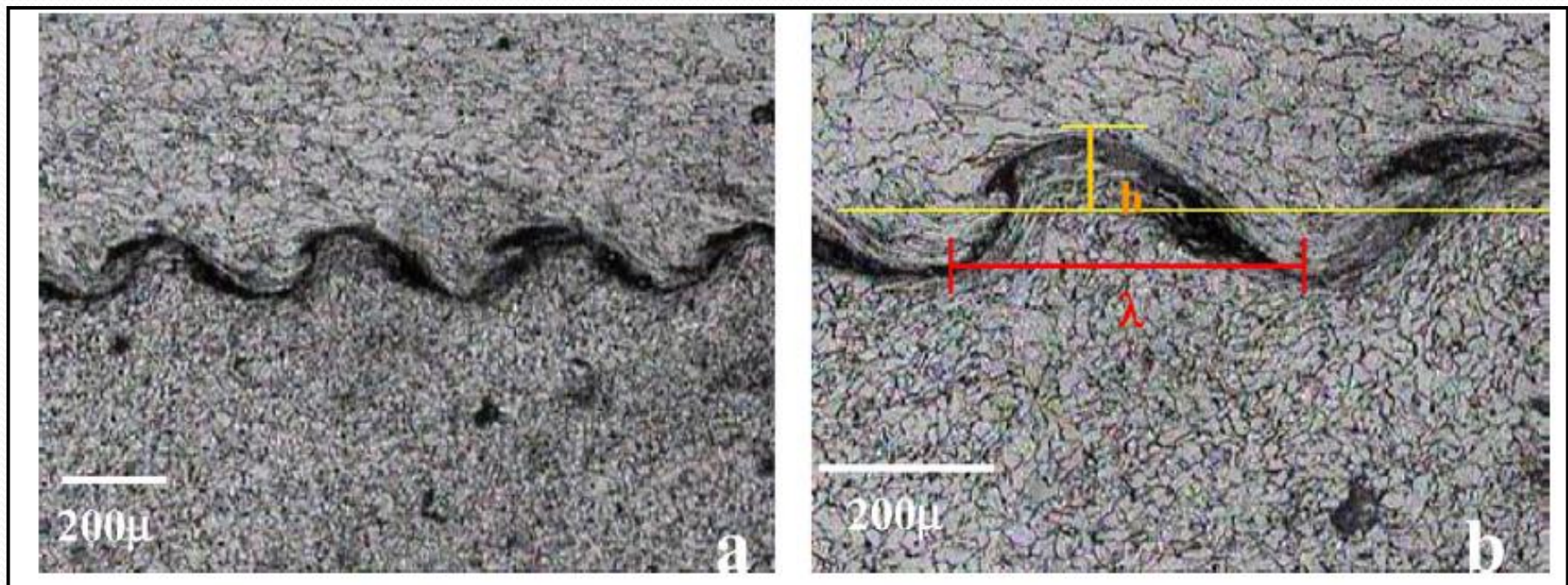
## CASO III – TORRE COM CHAPA CLADEADA



CLADEAMENTO POR EXPLOSÃO

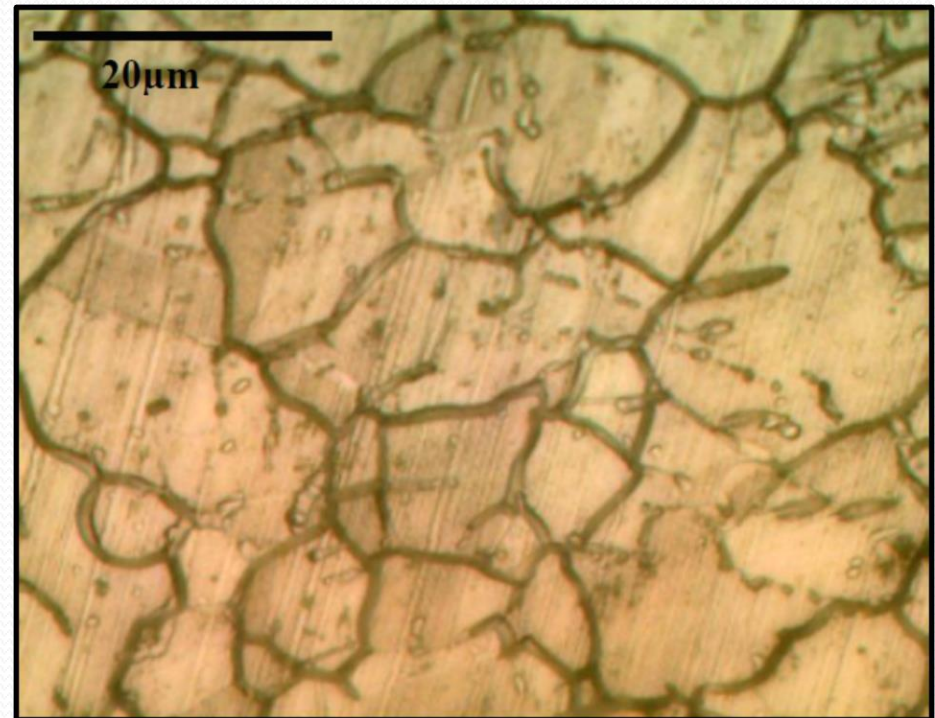
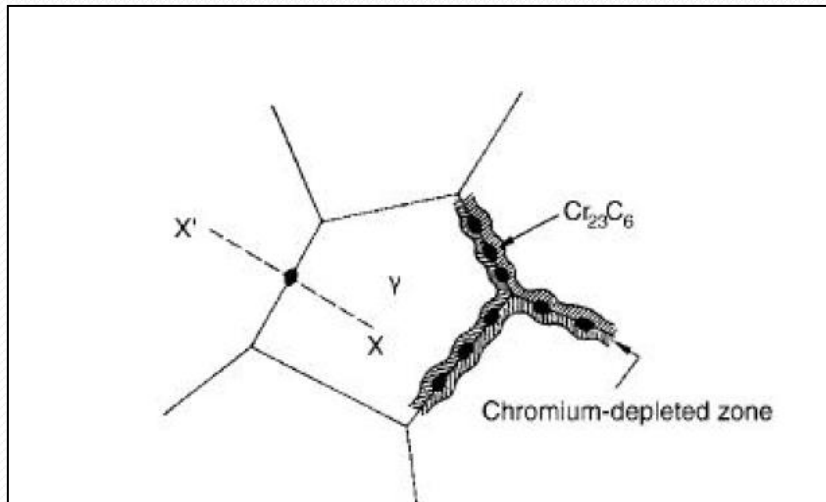


## MICROESTRUTURAS DO METAL BASE E CLADD POR EXPLOSÃO.



# CONSEQUÊNCIAS NECESSIDADE DE ALÍVIO DE TENSÕES EM 600°C

  
SENSITIZAÇÃO



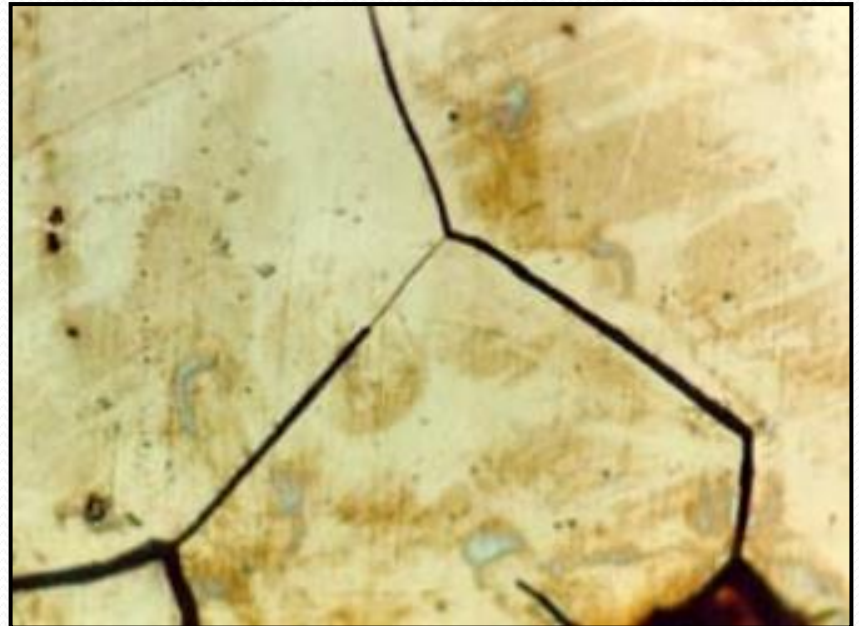
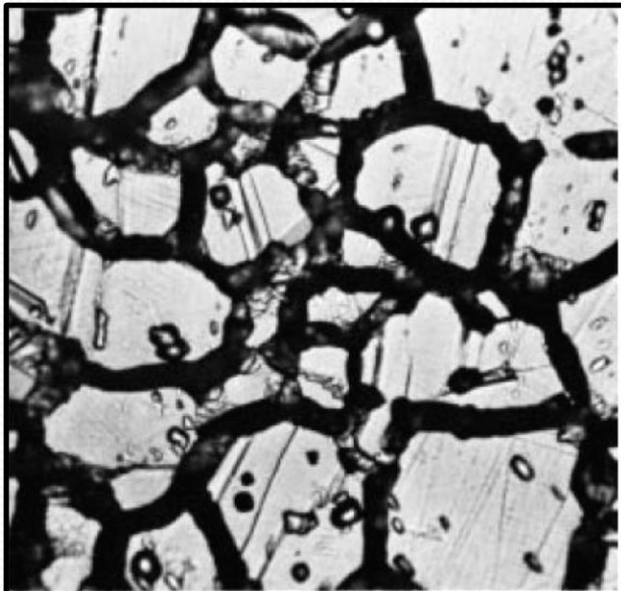
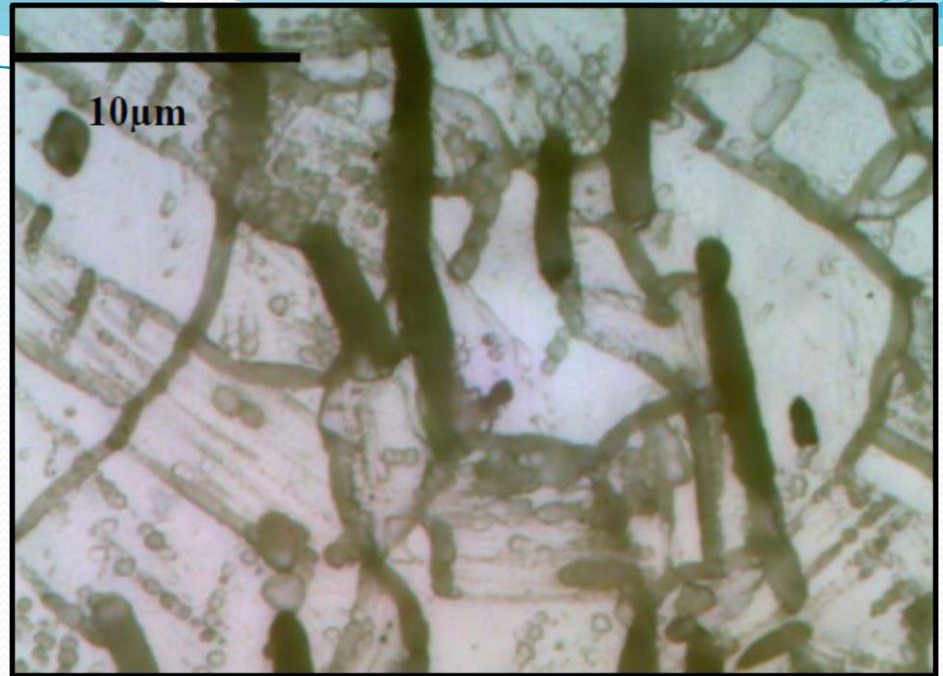
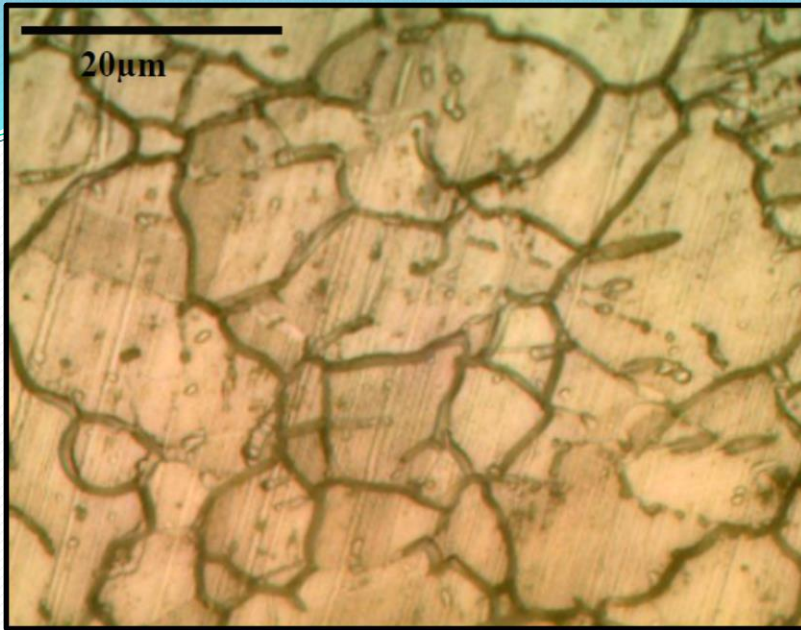


FIG. 3 Ditch Structure (500×) (One or more grains completely surrounded by ditches)

ASTM A 262-Fig.3 page 4.





**Figura 2**

Vista da região dobrada do corpo-de-prova.

**O MICROMECHANISMO DE FRATURA DEVERIA SER INTERGRANULAR.**

**FOI REALIZADA ANÁLISE DE MEV POIS AO MICROSCÓPIO ÓPTICO SERIA IMPOSSÍVEL SABER SE ERA INTERGRANULAR**

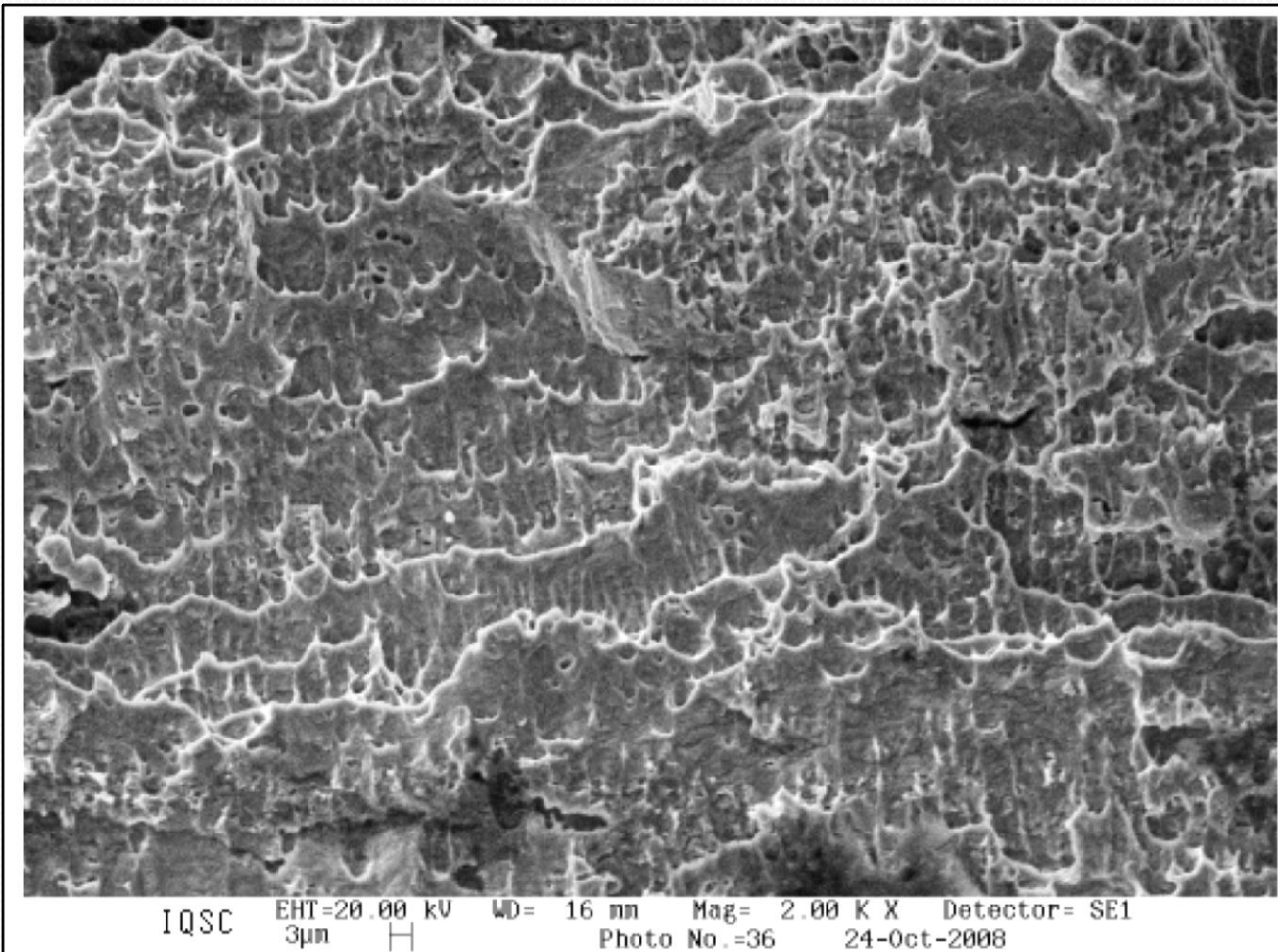
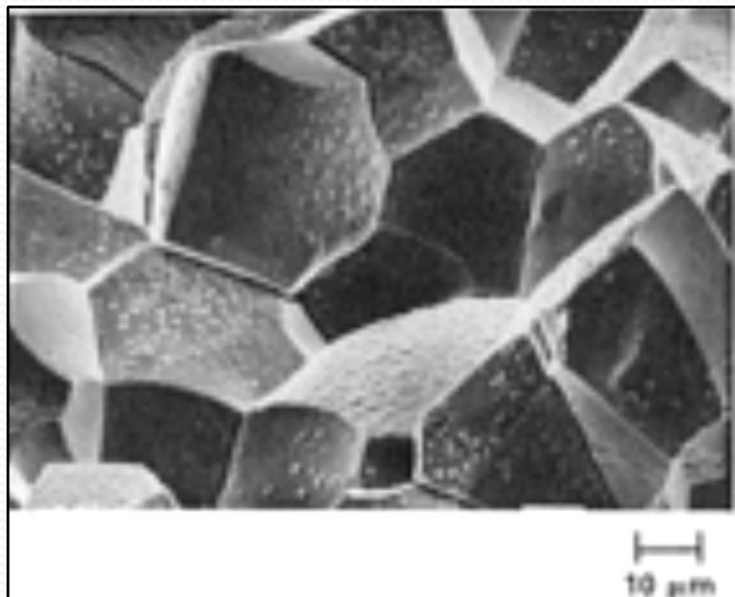


Figura 7 – Análise de MEV apresentando micromecanismo de fratura por “dimples”

**ESTE DEVERIA SER O MICROMECHANISMO DA  
CORROSÃO INTERCRISTALINA**



Corrosion products on the intergranular fracture surface of an Nb-106 alloy

**AÇÕES:**

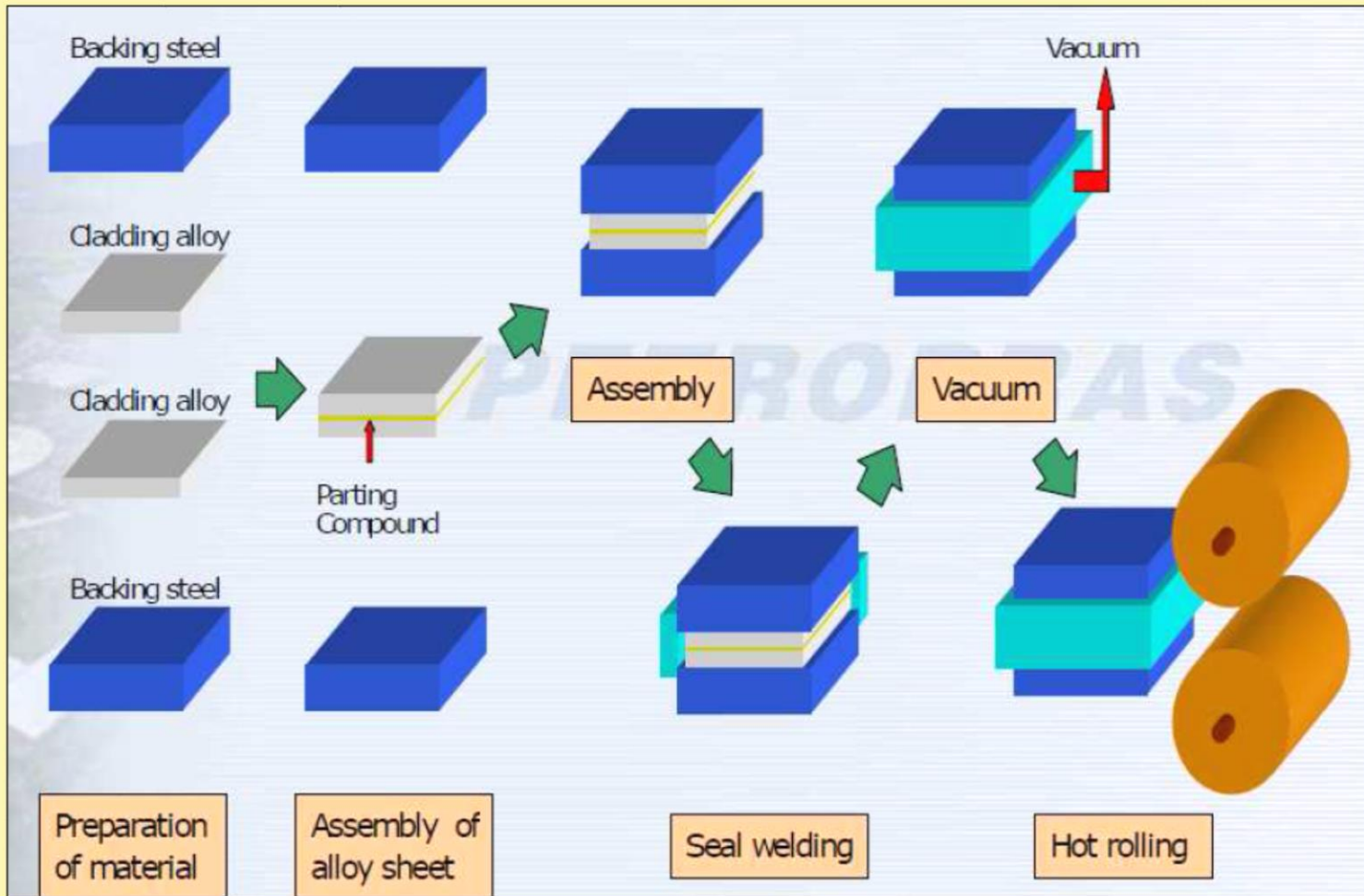
- **REUNIÃO COM A REPLAN EXPLICANDO O FENÔMENO;**
- **QUESTÃO: POR QUÊ A DUTILIDADE CAIU APÓS O CLADDING E ALÍVIO DE TENSÕES?**
- **PARA EVITAR NOVOS PROBLEMAS: COMPRAR CHAPAS CLADEADAS POR COLAMINAÇÃO.**



# Desafios Específicos de Laminação



## Laminação de Chapas Bi-Metálicas:



**CHAPA COLAMINADA**



**EQUIPAMENTOS**  
**PETROBRAS**

**Normas:**

- IET
- ASME/ASTM
- NACE
- AXENS
- EN



**REATOR**



## Normas mais utilizadas nos reatores de cromo-molibdênio:

- I-ET-5000.00-2316-570-PPC-001
- I-ET-5000.00-2316-500-PPC-002
- ASTM A 387 (ASME SA 387)
- ASTM A 516 (ASME SA 516)
- ASTM A 105 (ASME SA 105)
- ASTM A 240 (ASME SA 240)
- ASTM A 20 (chapas de aço carbono)
- ASTM A 370 ( ensaios mecânicos)
- ASTM E 21 (ensaio de tração a quente)
- ASME -Sec.II-Parte D - Tabela U e Y.
- ASTM E 23 (ensaio de impacto)
- ASTM A 262 (corrosão intergranular de aço inox)
- ASTM A 264 (ensaios de chapas cladeadas)
- ASTM G 146 (HID)
- N- 1704 (vasos com serviço H<sub>2</sub>)
- N- 1706 (vasos com serviço H<sub>2</sub>S)
- NACE TM 0284 (HIC)
- NACE TM 0177 (SSC)
- ASTM A 388 (US-Forjados)
- ASTM A 578 (US-Chapas)
- ASTM A 1268-(alinhamento de estrutura - Forjados)
- EN473 (qualificação de pessoal de NDT)

## **SPWHT para chapas de Cr-Mo:**

Heat Treatment: according to AF- 402.1 of ASME VIII Div. 2

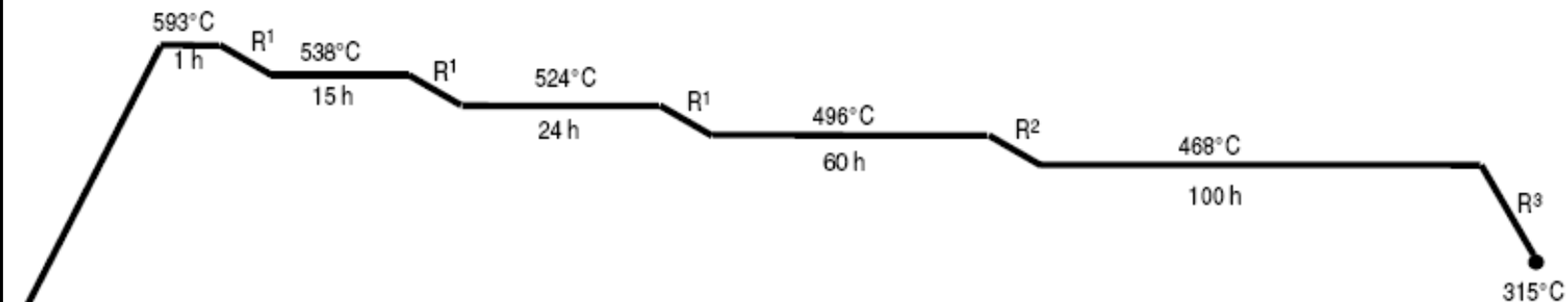
The heat treatment of the test coupons must be performed at 4 cycles of 105 minutes in the Holding temperature of 690°C (-0/+10°C); it will be not acceptable 1 cycle with total time for Heat treatment in test coupons. The plates shall be quenched or normalized and tempered above 690°C (-0/+10°C).

O ensaio de **dureza** é realizado após o **primeiro ciclo** do SPWHT e deve ser realizado em **5 pontos a 2 mm da superfície e a ¼ (t < 55mm) ou 1/2 da superfície (t > 55mm)**, conforme prevê a IET. Os **outros ensaios** devem ser realizado após os **4 ciclos de SPWHT**.

- **SUBMETER COUPONS DO MATERIAL AO SPWHT;**
- **ALGUNS COUPONS JÁ COM SPWHT SUBMETER AO STEP COOLING.**

Step Cooling Procedure (from WRC Bulletin # 275 – Feb./1982):

Temperature [ °C ]	Holding time [ hours ]	Cooling rate to next temperature [ °C per hour ]
593	1	5.6
538	15	5.6
524	24	5.6
496	60	3.0
468	100	27.8
315	then air cool	



R<sup>1</sup> = Cooling rate = 5.6°C/h  
 R<sup>2</sup> = Cooling rate = 3.0°C/h  
 R<sup>3</sup> = Cooling rate = 27.8°C/h

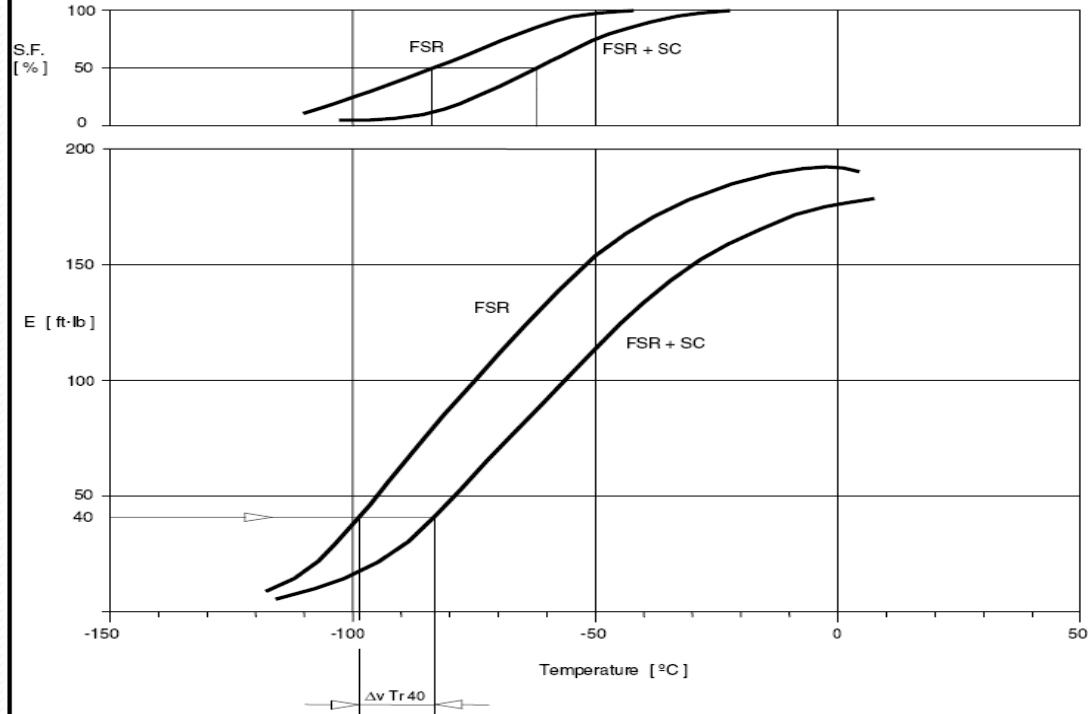
Temperature uniformity : ±10°C

- **Cinco sets de três corpos de prova cada um, que já sofreram SPWHT e Step Cooling e cinco sets com cps cada um só com SPWHT;**
- **Ensaio de impacto em cinco temperaturas diferentes, sendo que uma delas deve ser -18°C para o ASTM A 387 – Gr.11(1,25Cr-0,5Mo);**
- **Levanto a curva de energia absorvida por temperatura de impacto;**



PETROBRAS

APPENDIX I: Typical Impact Transition Curves



RESULT :

v Tr 40 (FSR)	v Tr 40 (SC)	$\Delta v Tr 40$	v Tr 40 + 2.5 $\Delta v Tr 40$	RESULT
-98°C	-82°C	16°C	-58°C	ACCEPTABLE

CONVENTION :

- FSR : Fully Stress Relieved
- SC : Step Cooling
- S.F. : Shear Fracture
- E : Absorbed Energy

# Cálculo do deslocamento da curva de temperatura de transição frágil-dútil do material com e sem step-cooling.

Acceptance criteria for 2.25Cr-1Mo material shall be in accordance with the following formula based upon the embrittlement shift value due to step cooling.

$$\text{Shift value} = (v \text{ Tr } 40) + 2.5 \times (\Delta v \text{ Tr } 40 \text{ Sc}) < 10^\circ\text{C}$$

Where:  $v \text{ Tr } 40$  = transition temperature at absorbed energy of 40 ft·lb of completely heat treated specimens;

$\Delta v \text{ Tr } 40 \text{ Sc}$  = shift in 40 ft·lb transition temperature due to step cooling.

For 1.25Cr-0.5Mo, the shift value due to step cooling shall be calculated **only for information**, using the equation mentioned above.

## b) – Chemical analysis

Chemical analysis shall conform to ASME SA-387 Gr. 11 or Gr. 22 specifications but, when the operating temperature of components exceeds 350°C, for 2 1/4Cr -1Mo the *J*-factor shall be verified as follows:

$$J = (Si + Mn) \times (P + Sn) \times 10^4 = 100 \text{ max. (target value: 80)}$$

For 1 1/4Cr – 1/2Mo base material the *J*-factor shall be calculated as below:

$$J = (Si + Mn) \times (P + Sn) \times 10^4 = 220 \text{ max. (target value: 180)}$$

**PREVISÃO DA SENSIBILIDADE DO MATERIAL À  
FRAGILIZADADE AO REVENIDO PELA COMPOSIÇÃO  
QUÍMICA:**

**FATOR J – WATANABE  
FATOR X - BRUSCATTO**



**FIM**