



# PME 3430

## *Materials 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**

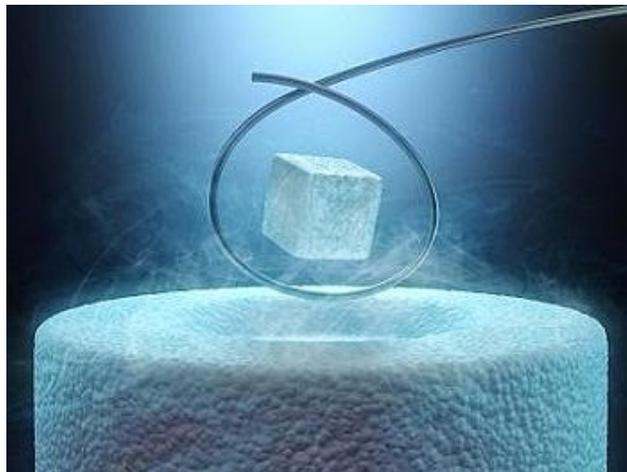
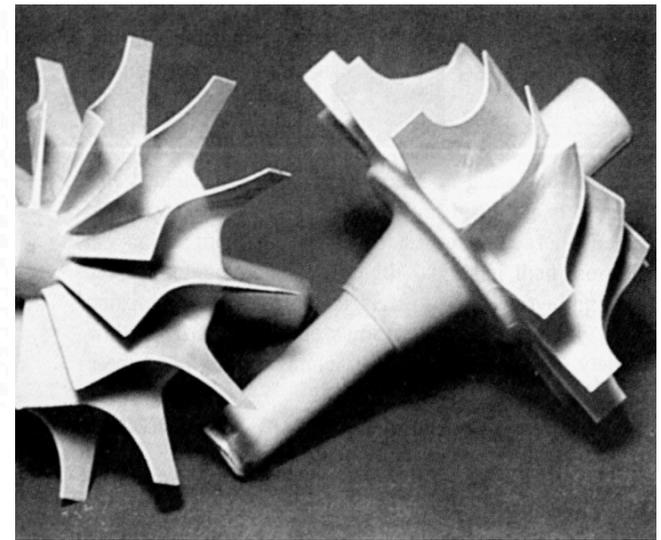


# Cronograma de Atividades – 1º Semestre 2017

## 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	<b>SEMANA SANTA – Não haverá aula</b>
06	19/04	Tratamento de superfícies de ligas metálicas (químico e mecânico)
07	26/04	Ligas contra corrosão (Aço Inox)
08	03/05	Aula de exercícios
09	10/05	<b>PROVA – P1 e entrega de TRABALHOS – T1</b>
10	17/05	Processamento de Polímeros (polimerização, vulcanização, temperatura vítrea)
11	24/05	Processamento de Cerâmicas (fundição, sinterização, tratamento térmico)
12	31/05	Cerâmicas avançadas (piezos e termo-elétricos)
13	07/06	Recobrimentos cerâmicos (carbonetos, nitretos, óxidos)
14	14/06	Compósitos metal/polímero/cerâmicos (fibras de carbono, aramida)
15	21/06	Aula de exercícios
16	28/06	<b>Entrega de TRABALHOS – T2</b>
17	05/07	<b>PROVA – P2</b>
18	07/07	<b>PROVA Substitutiva</b>

# Materiais cerâmicos



[http://supercondutividade.blogspot.com.br/2015/02/01\\_archive.html](http://supercondutividade.blogspot.com.br/2015/02/01_archive.html) acessado em 03/2017

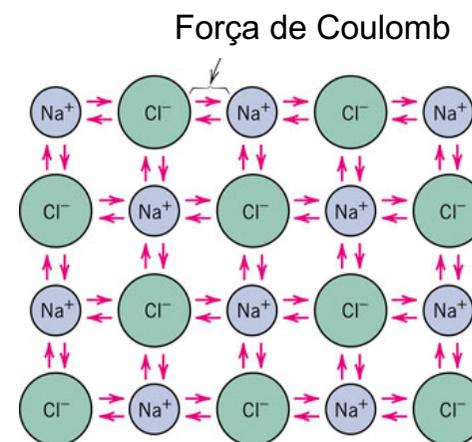
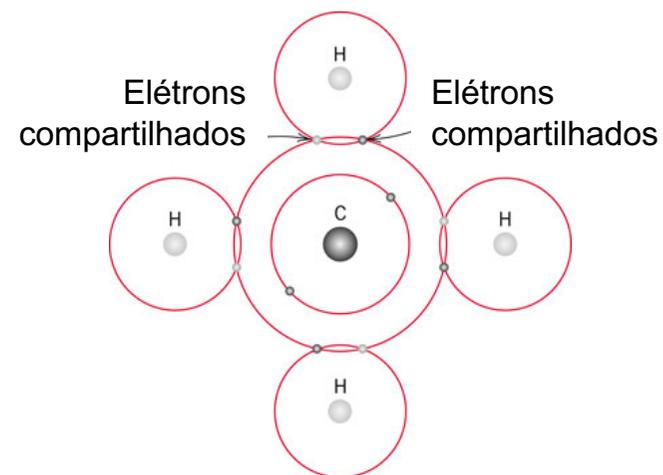


[https://en.wikipedia.org/wiki/Space\\_Shuttle\\_thermal\\_protection\\_system](https://en.wikipedia.org/wiki/Space_Shuttle_thermal_protection_system) acessado em 03/2017



# Ligações atômicas

Material	Porcentagem do caráter iônico
$\text{CaF}_2$	89
$\text{MgO}$	73
$\text{NaCl}$	67
$\text{Al}_2\text{O}_3$	63
$\text{SiO}_2$	51
$\text{Si}_3\text{N}_4$	30
$\text{ZnS}$	18
$\text{SiC}$	12

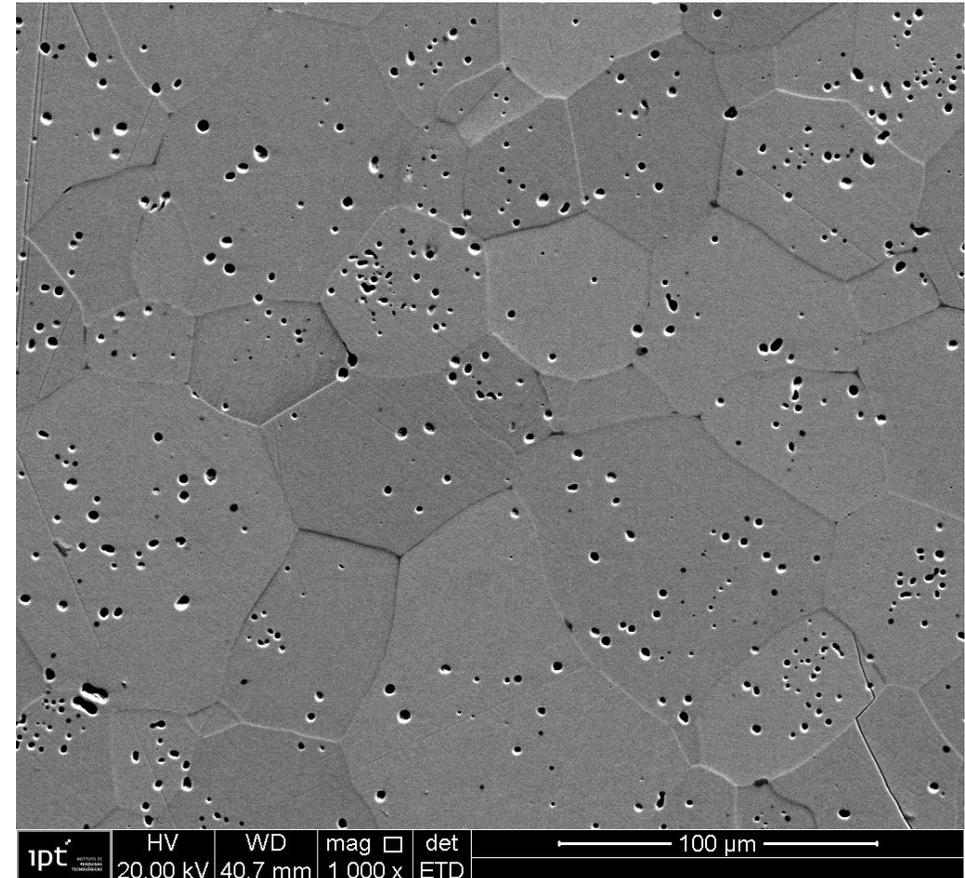
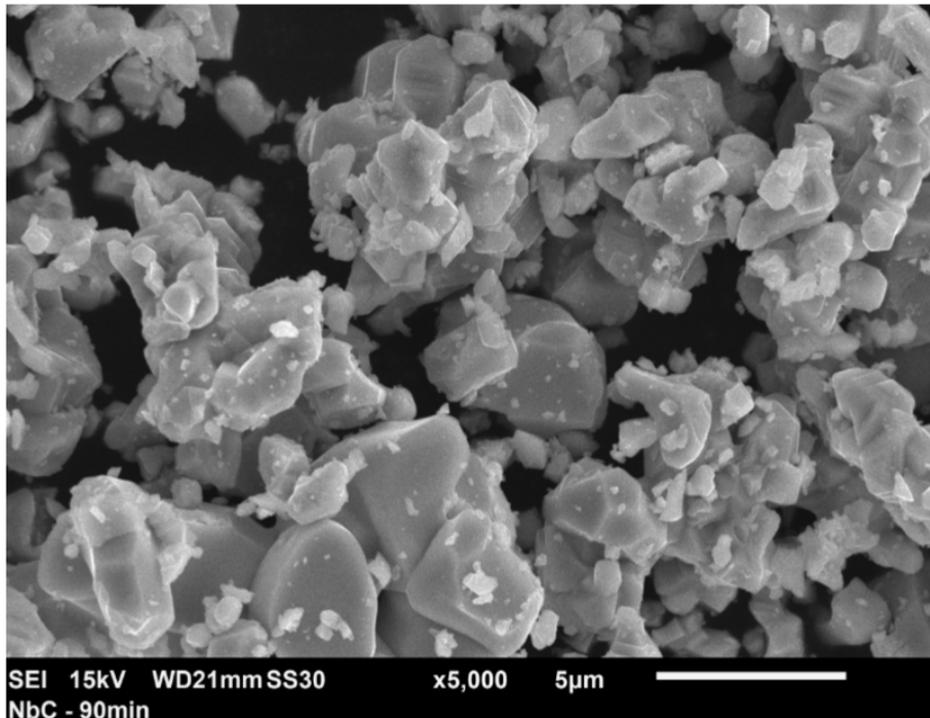




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# Microestruturas

## ❖ Carboneto de Nióbio (NbC)



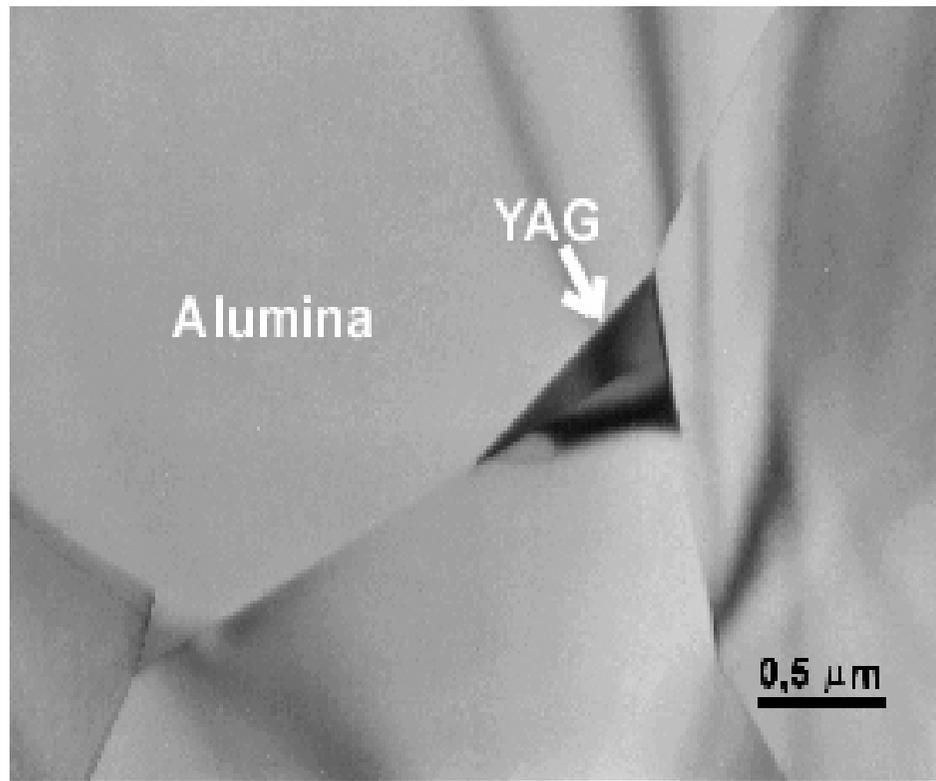


# Microestruturas

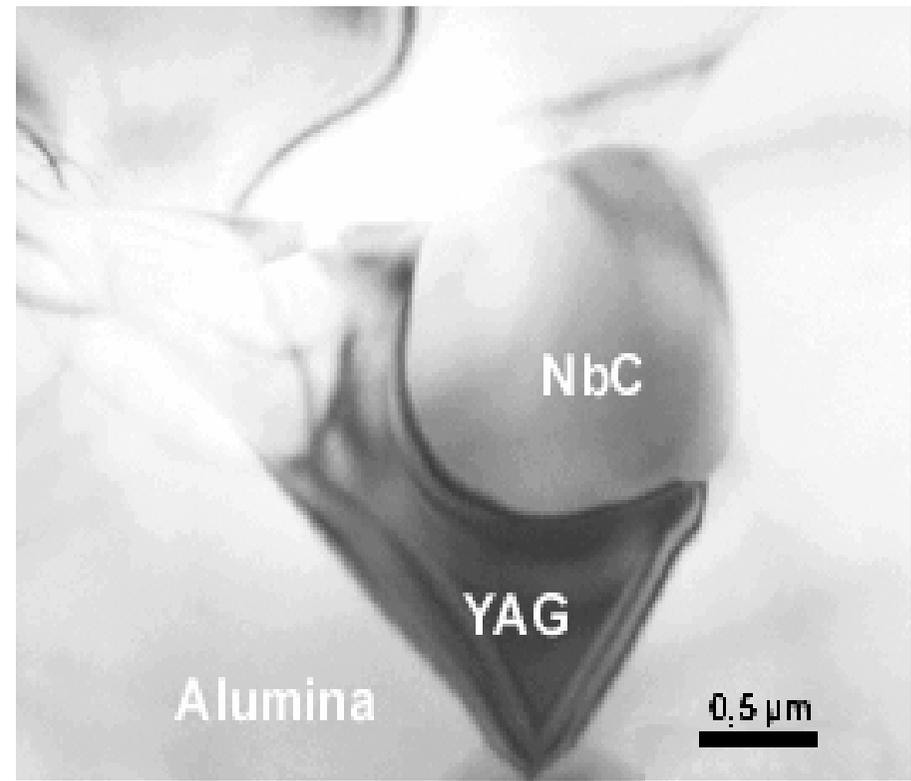
## ❖ Ytrium Aluminum Garnet (YAG)



❖ Fase ligante



Ferreira 2001





# Processamento de cerâmicas

❖ Fusão



❖ Secagem + Queima



❖ Metalurgia do pó

❖ Compactação a frio

❖ Compactação a quente



# ***Processamento de cerâmicas***

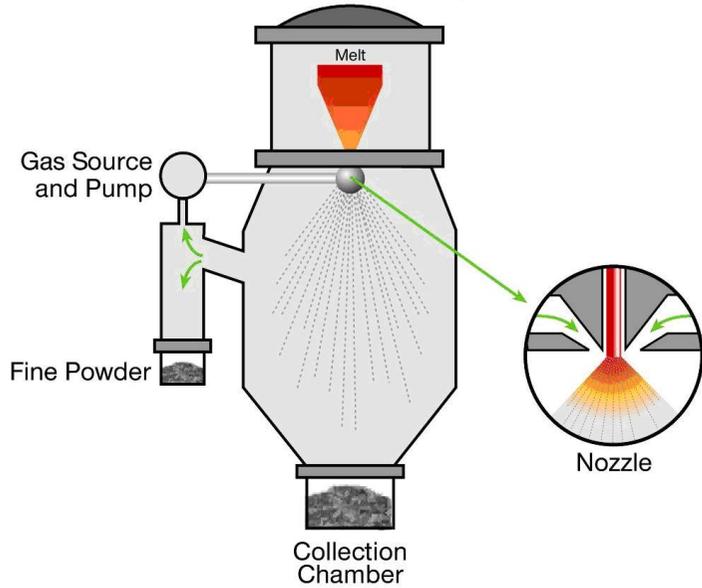
- ❖ **Metalurgia do pó**
  - ❖ **Produção do pó**
  - ❖ **Misturas**
  - ❖ **Secagem**
  - ❖ **Controle do tamanho do pó**
  - ❖ **Conformação + queima**
    - ❖ **Prensagem uniaxial ou isostática a frio**
    - ❖ **Extrusão**
    - ❖ **Injeção em molde**
  - ❖ **Conformação + sinterização**
    - ❖ **Prensagem uniaxial ou isostática a quente**



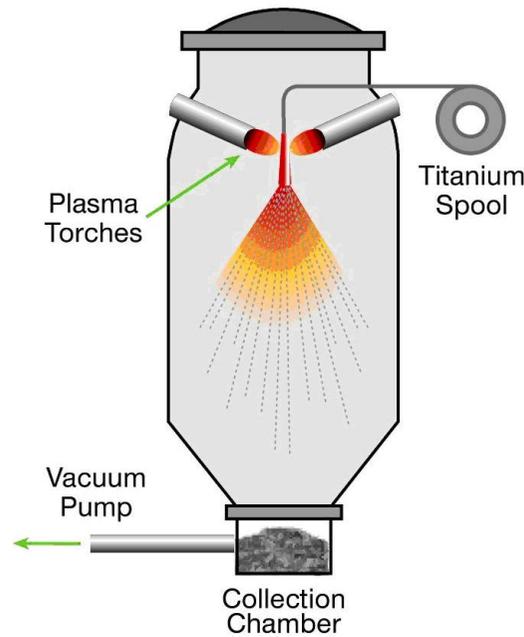
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# Processamento de cerâmicas

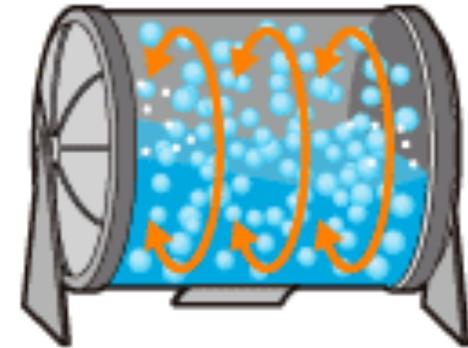
## Atomização



## Plasma



## Moagem mecânica

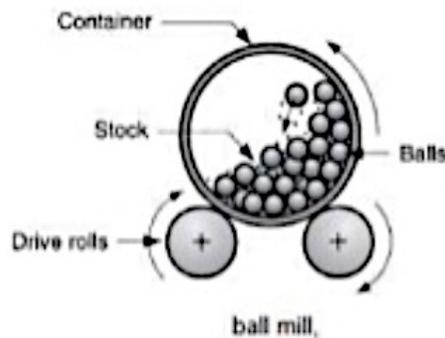


Raw Material  
Milling / Mixing

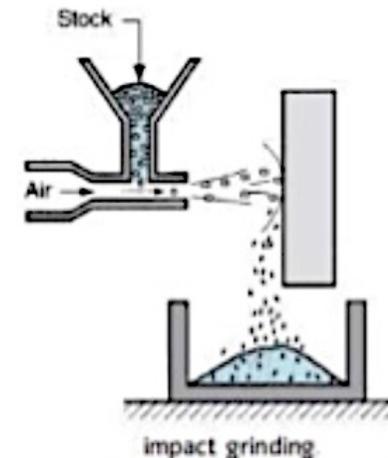
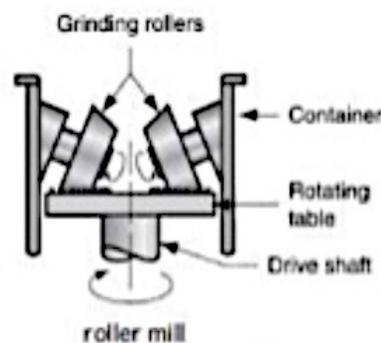
<http://www.lpwtechnology.com/technical-library/powder-production/>

## Cominuição por impacto

## Cominuição por esferas

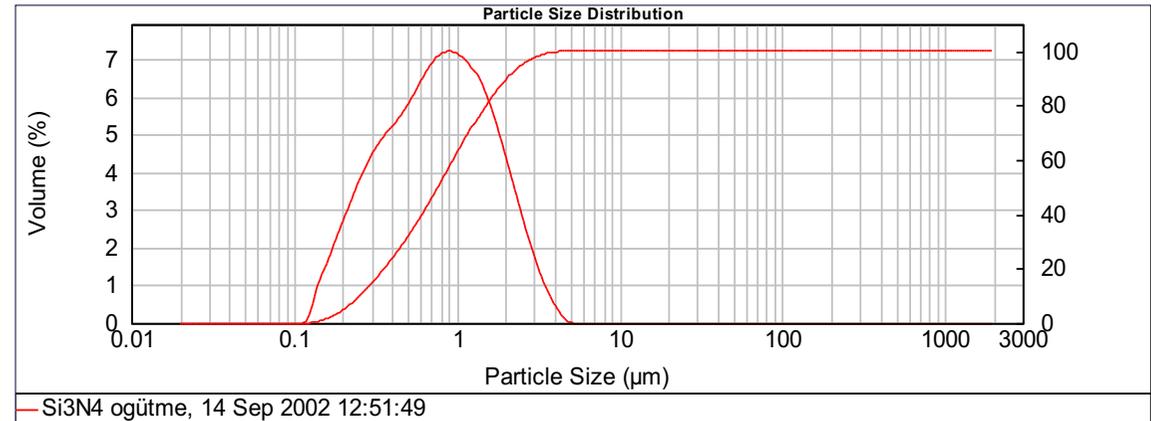
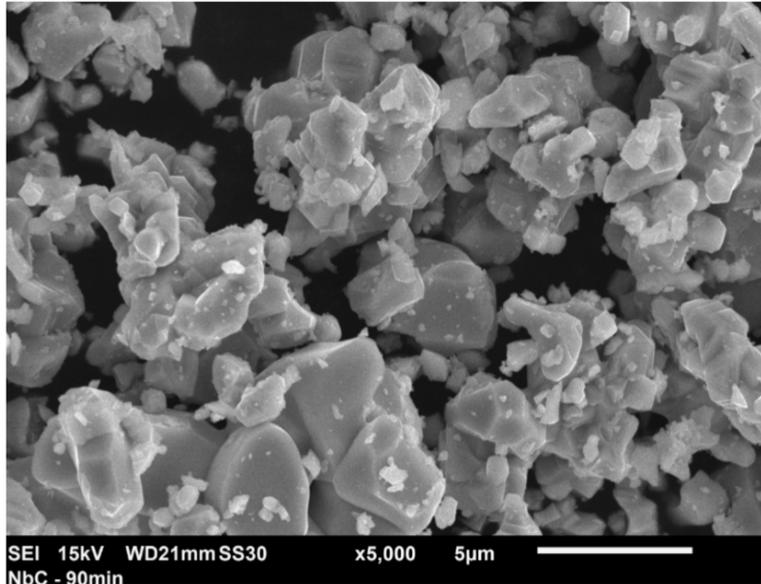


## Cominuição por rolos



<https://www.slideshare.net/shunty12/5-powder-metallurgy>

# Processamento de cerâmicas



Ferreira 2008

O pó resultante do processo de moagem e secagem deve ser "puro" e ter distribuição que minimize formação de poros na sinterização



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# Processamento de cerâmicas

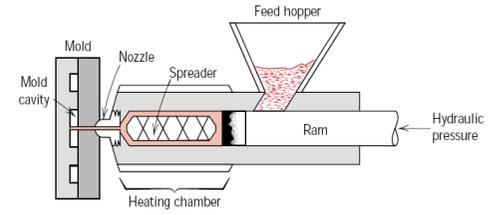
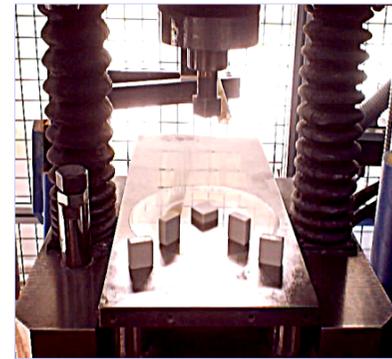
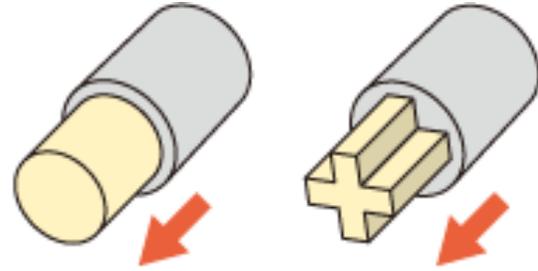
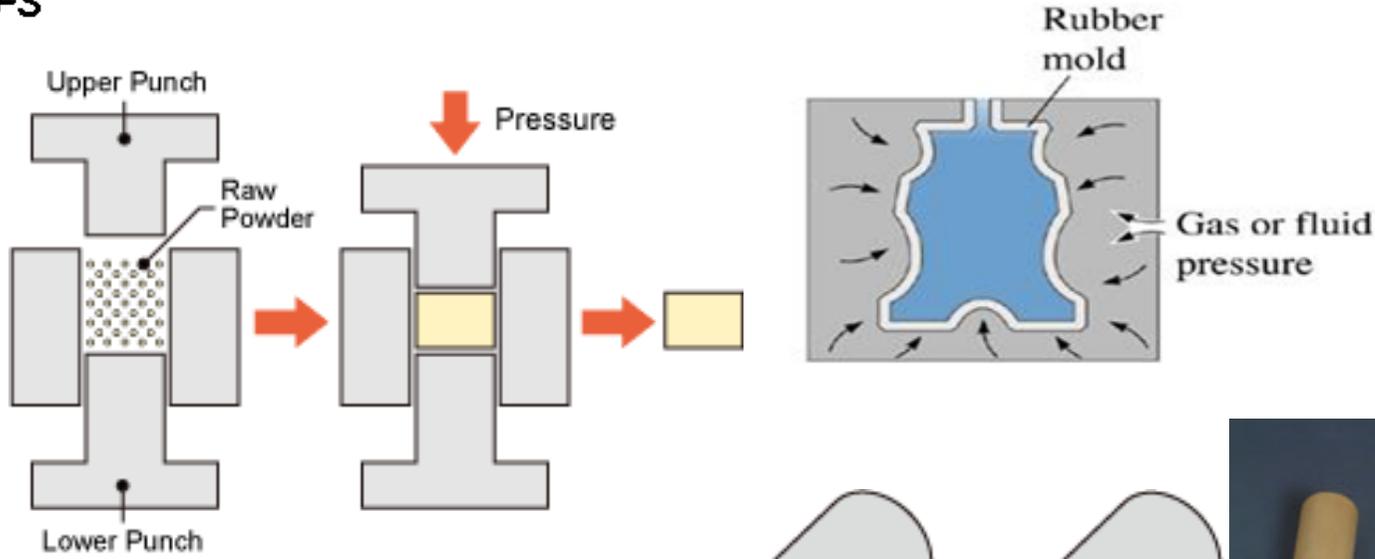
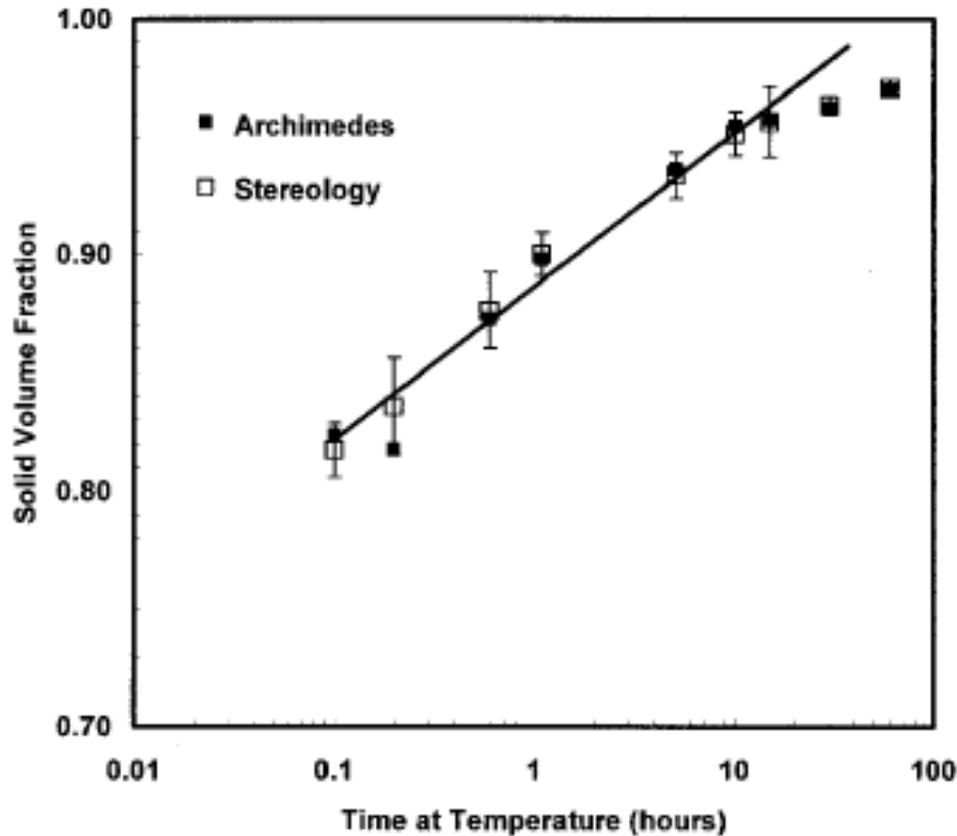
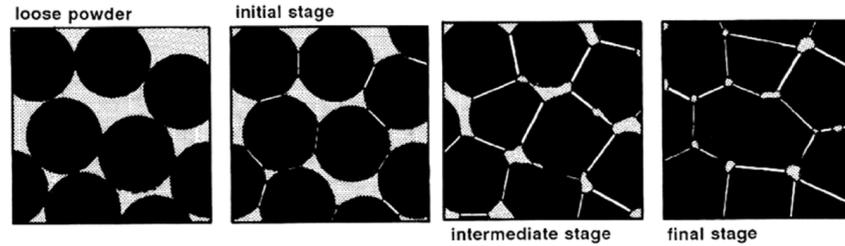


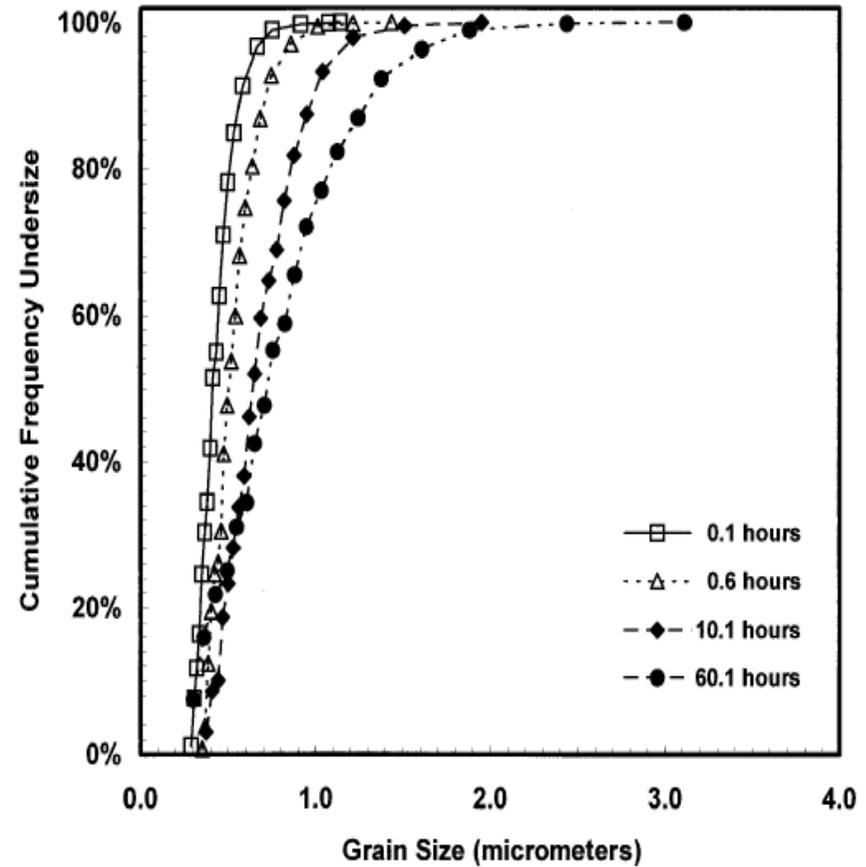
FIGURE 14.28 Schematic diagram of an injection molding apparatus. (Adapted from F. W. Billmeyer, Jr., *Textbook of Polymer Science*, 2nd edition. Copyright © 1971 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Ferreira 2008

# Processamento de cerâmicas



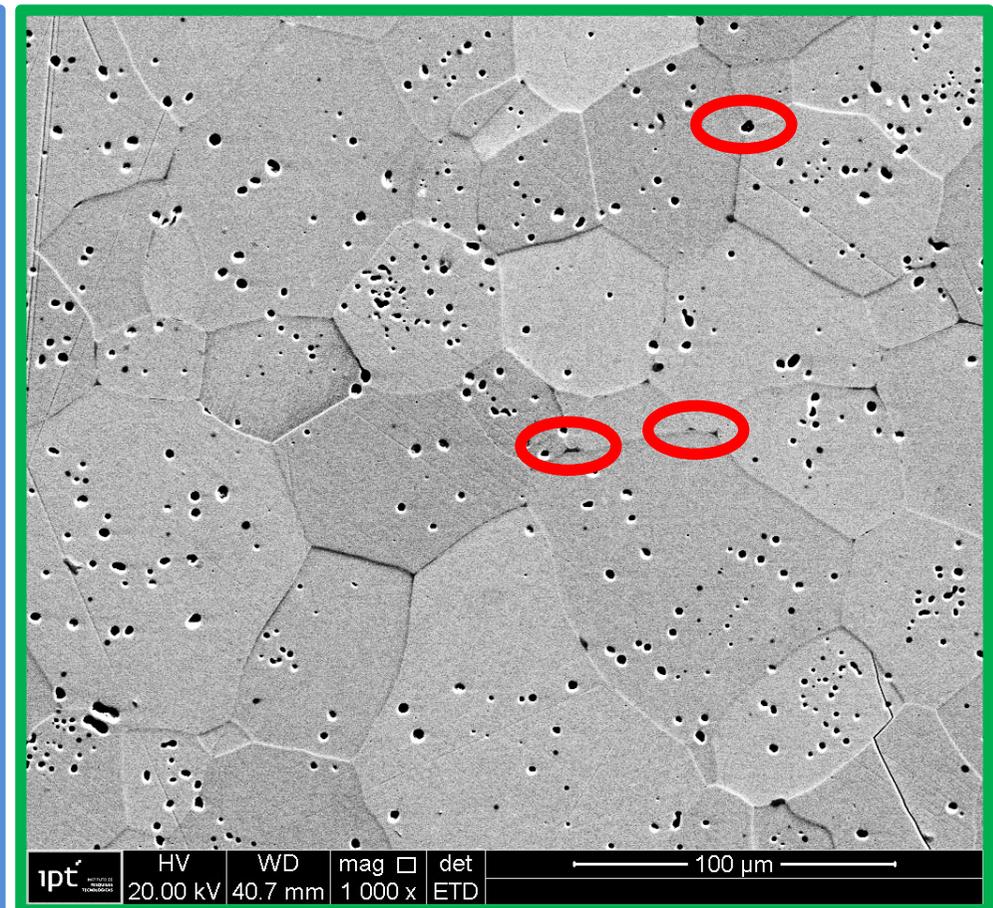
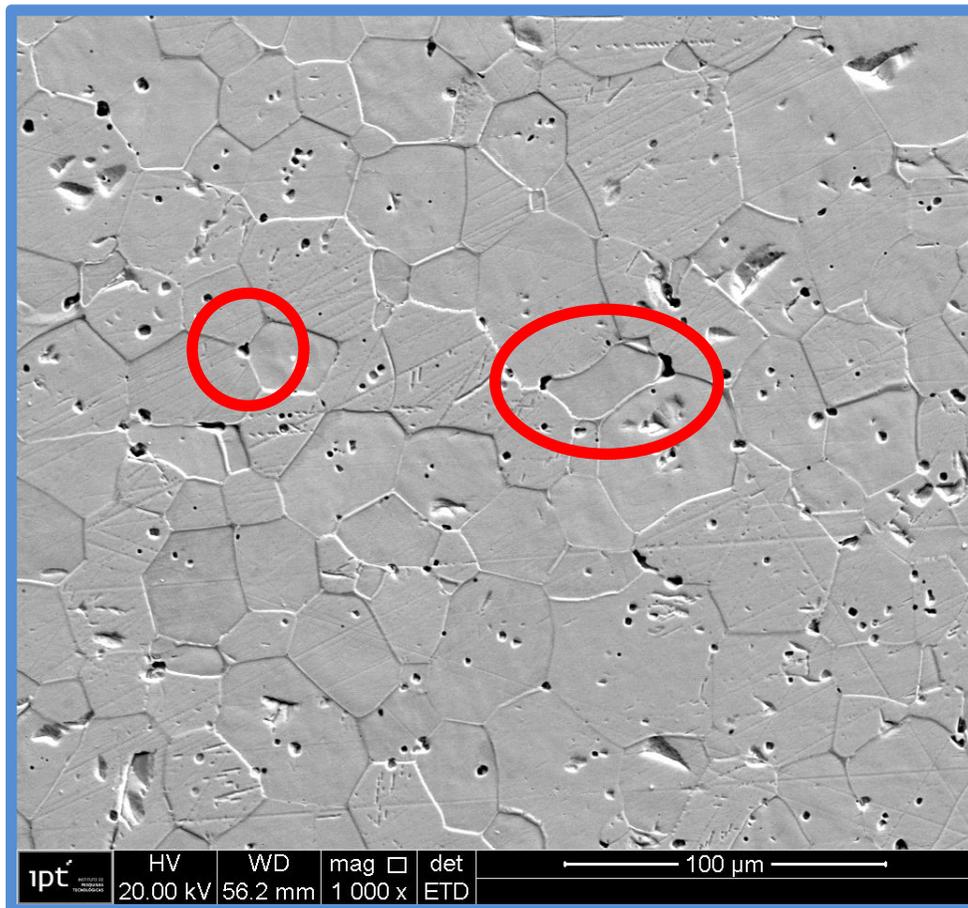
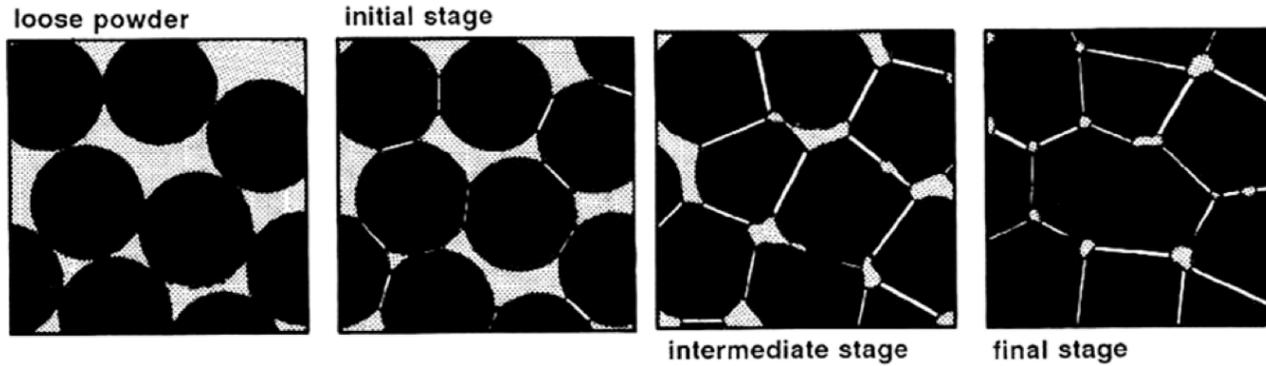
Efeito do tempo de sinterização na densidade



Efeito do tempo no tamanho de grão.

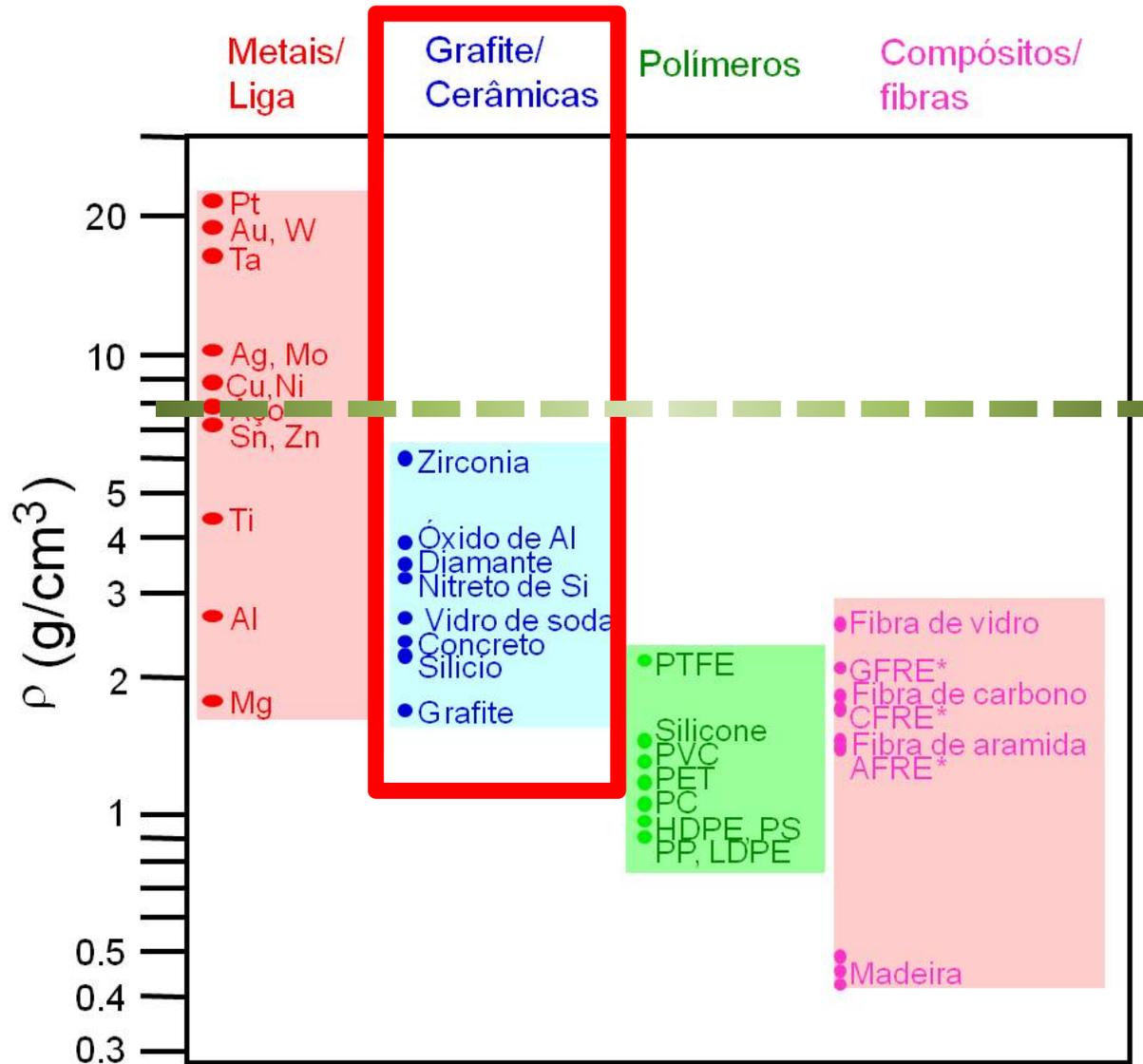


# Microestrutura de cerâmicas





# Tipos de materiais – Módulo elástico

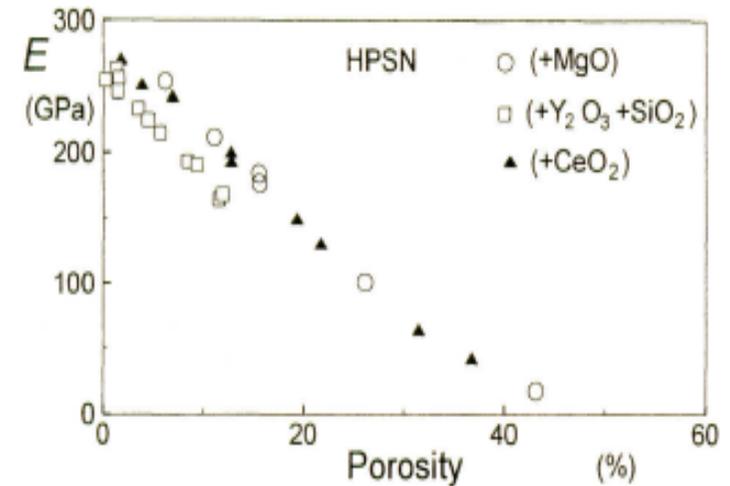
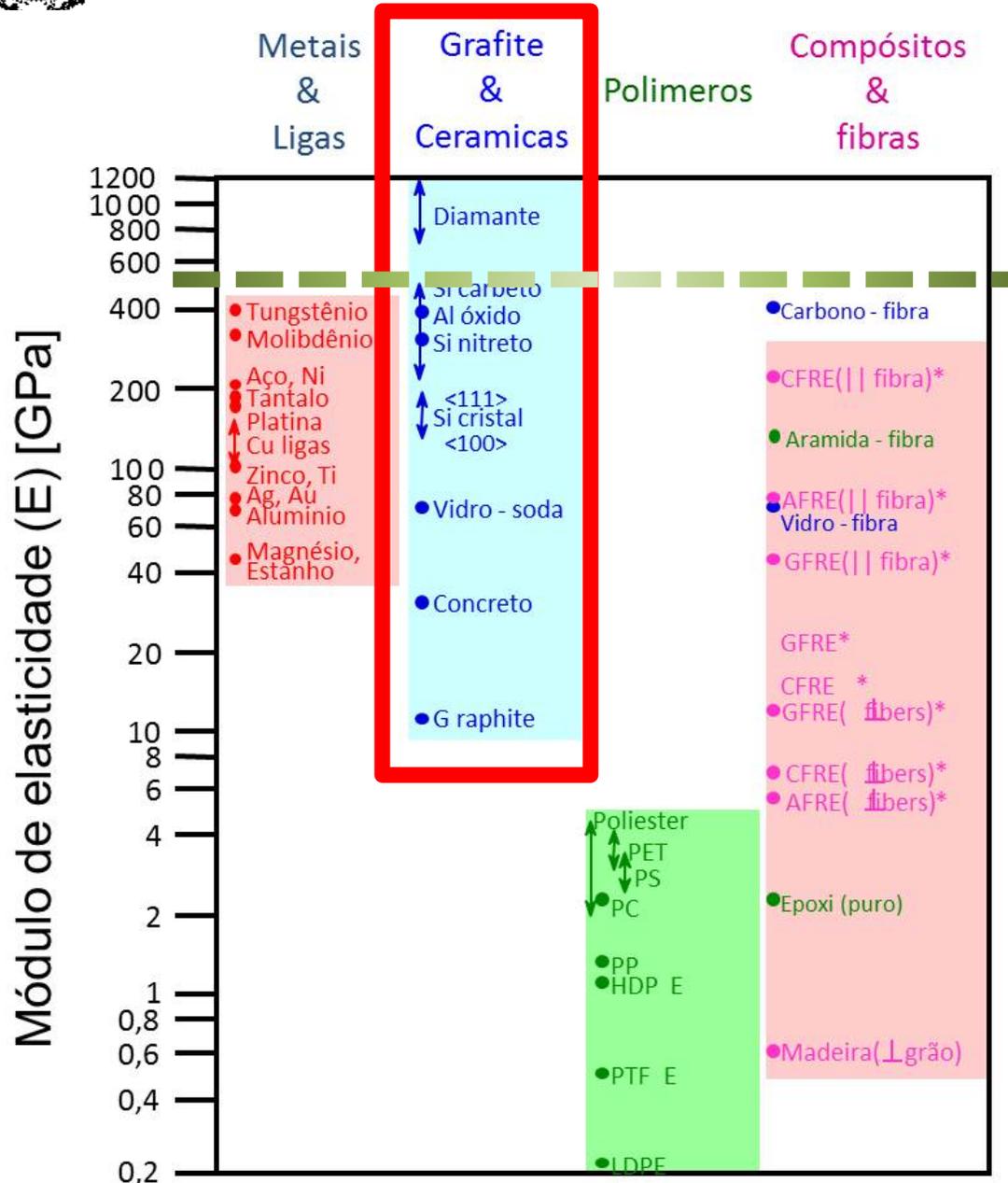


Exemplos

Cerâmica	$\rho$ (g/cm <sup>3</sup> )
Al <sub>2</sub> O <sub>3</sub>	3,9
SiO <sub>2</sub>	2,65
MgO	3,58
SiC	3,21
Si <sub>3</sub> N <sub>4</sub>	3,21
TiC	4,93
TiN	5,29
BN (hexagonal)	2,27
BN (cúbico)	3,48
NbC (cúbico)	7,82



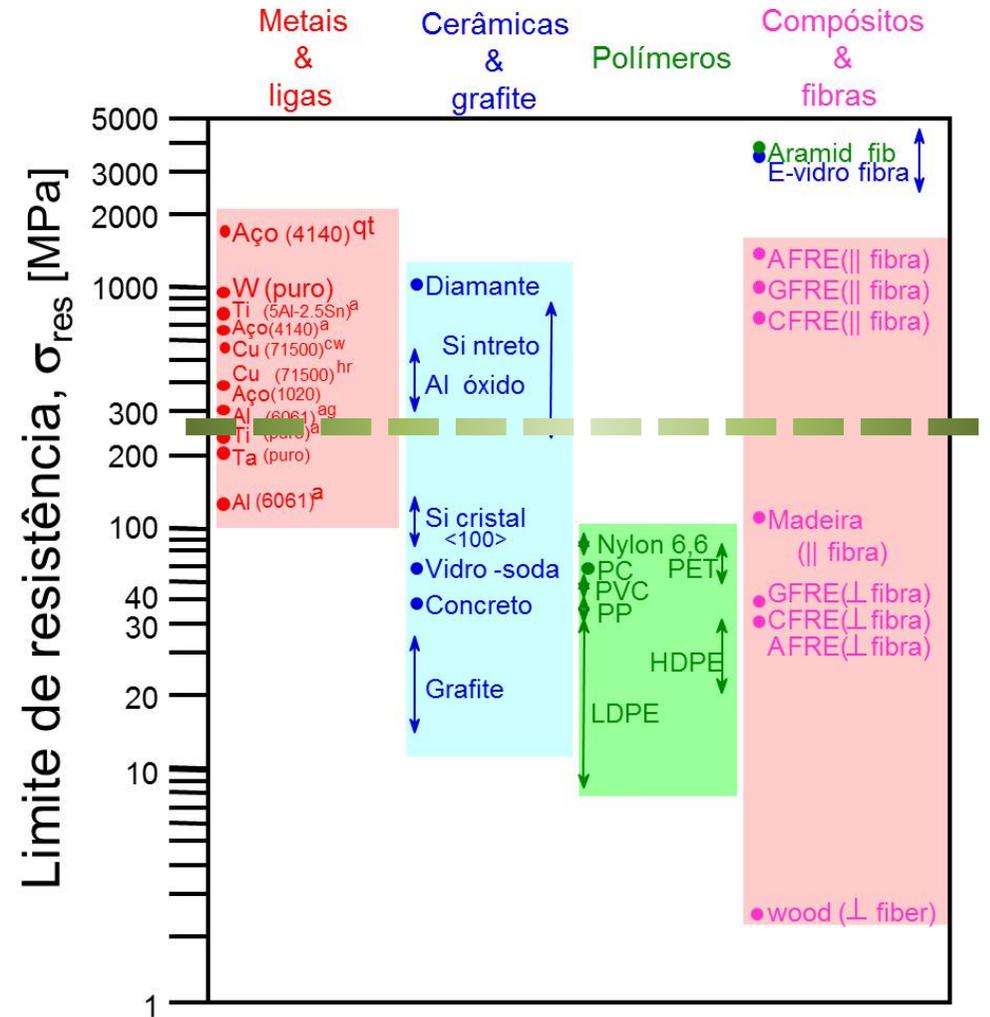
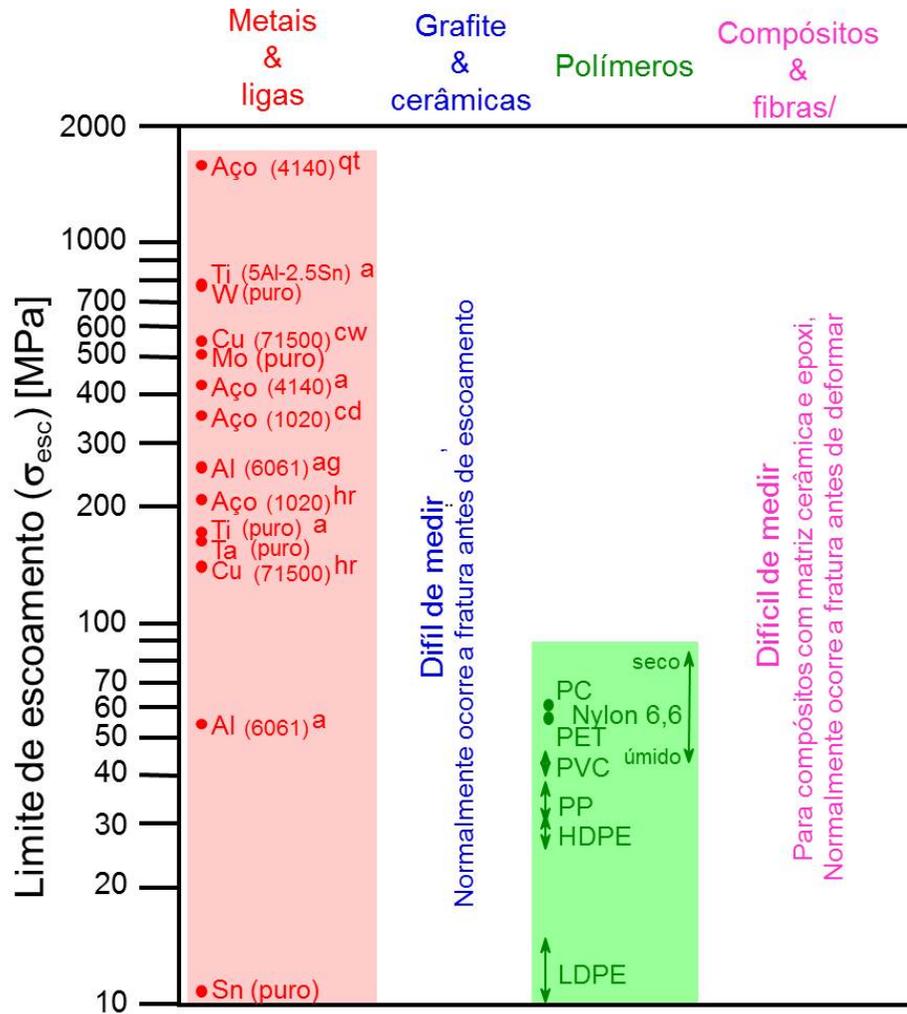
# Tipos de materiais – Módulo elástico



$E = E_0(1 - aP)$
$E = E_0(1 - aP + bP^2)$
$E = E_0(1 - aP)^b$
$E = E_0[1 + aP / (1 - (a + 1)P)]$
$E = E_0 \exp(-aP)$
$E = E_0 \exp[-(aP + bP^2)]$



# Tipos de materiais – Limite de Escoamento





# Comportamento de falha

## ❖ Tenacidade à fratura

### ❖ Inglis

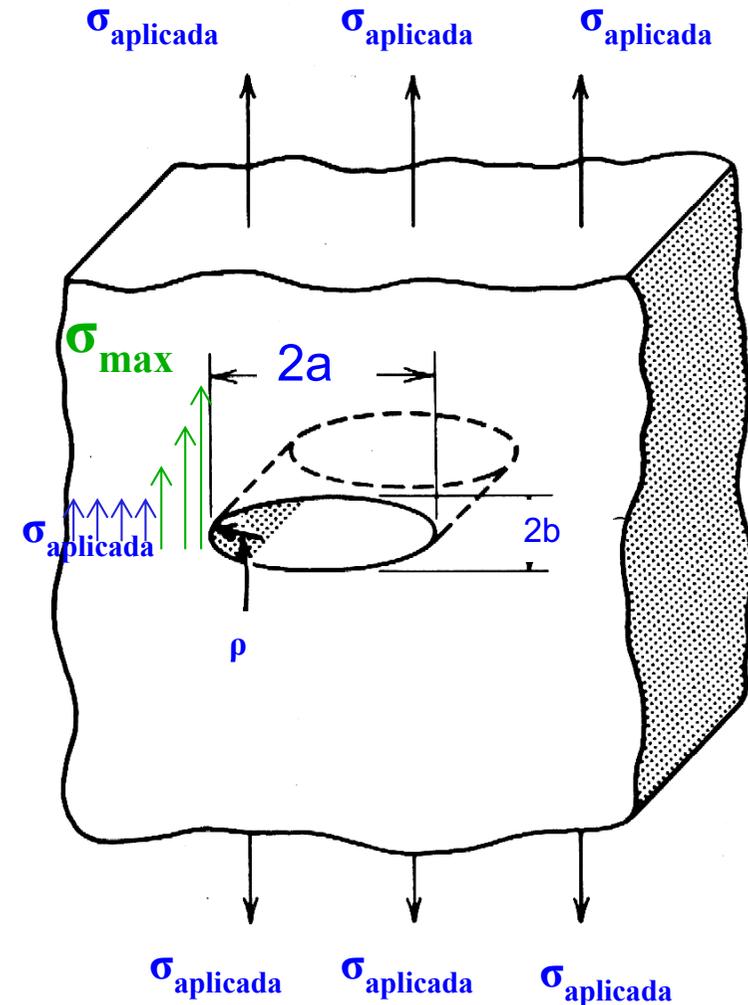
$$\sigma_{max} = \sigma_{aplicada} \left( 1 + 2 \sqrt{\frac{a}{\rho}} \right)$$

### ❖ Griffith

$$\sigma_{fratura} = \sqrt{\frac{2E\gamma_s}{\pi a}}$$

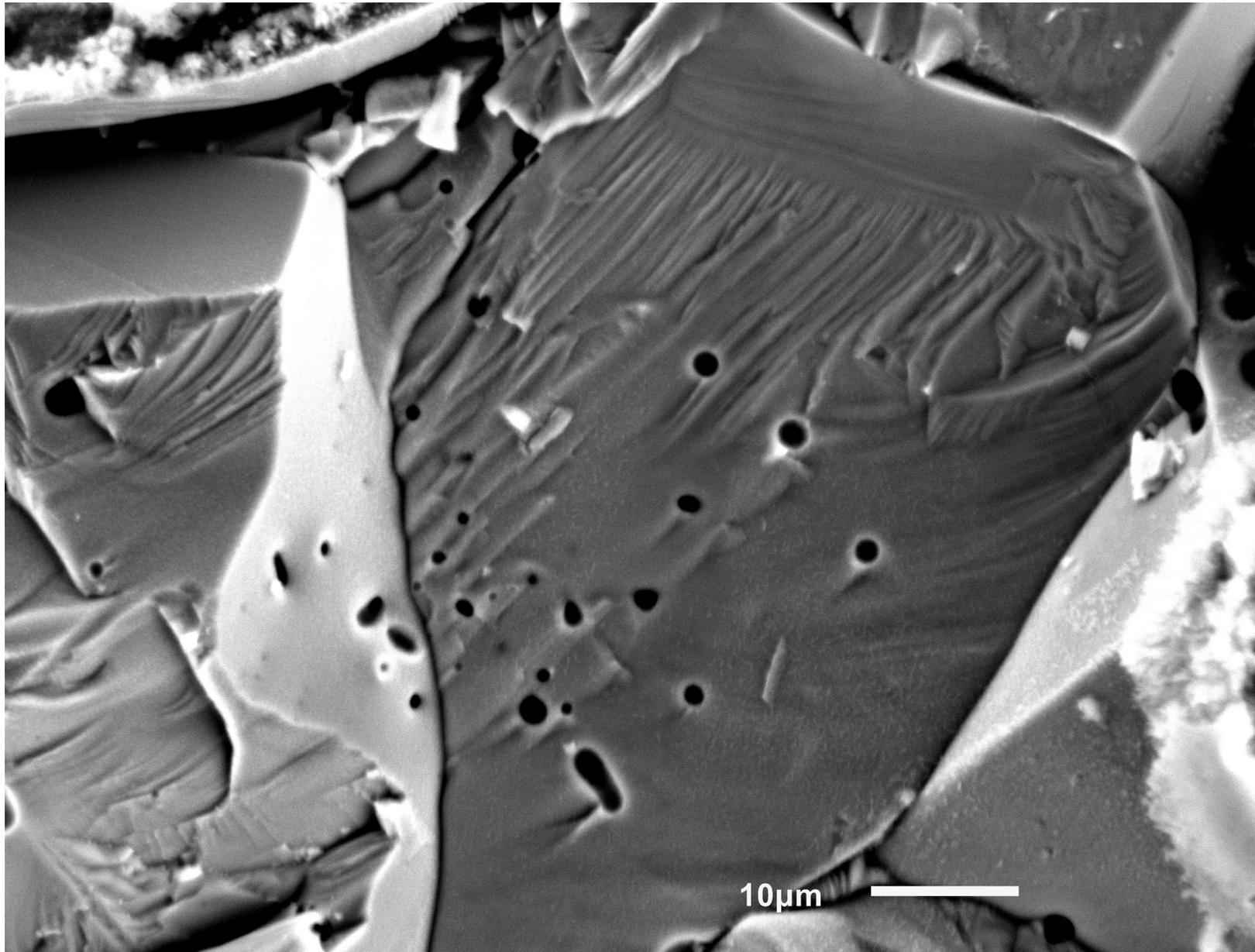
### ❖ Irwing

$$K_c = \sigma_c \sqrt{\pi a}$$



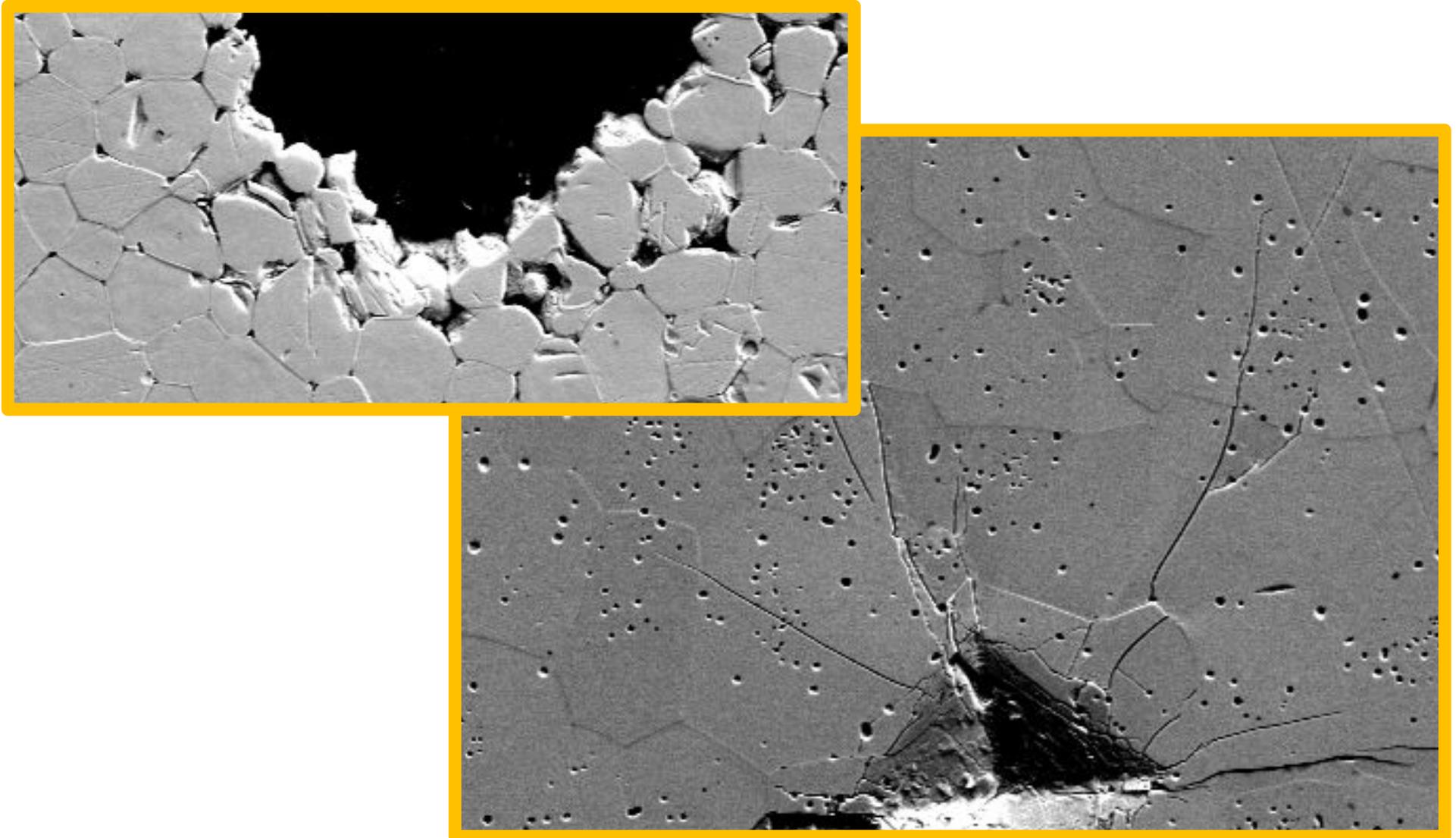


# Comportamento de falha





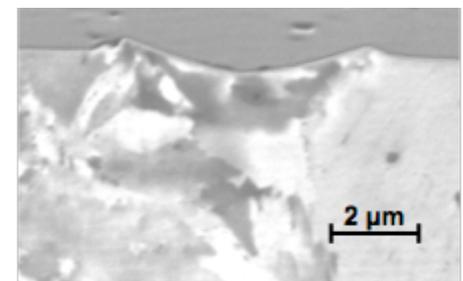
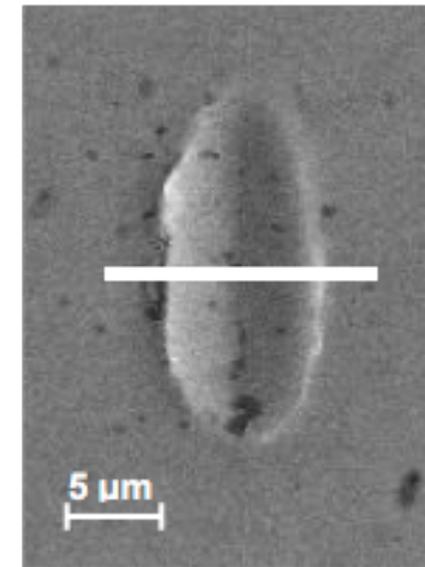
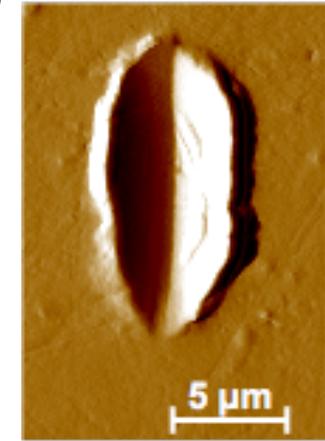
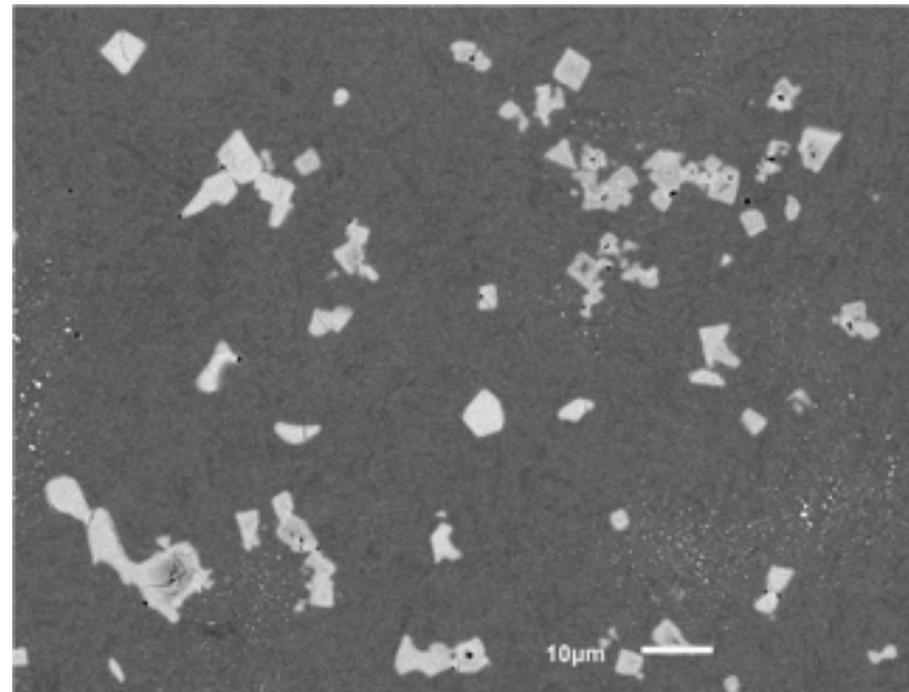
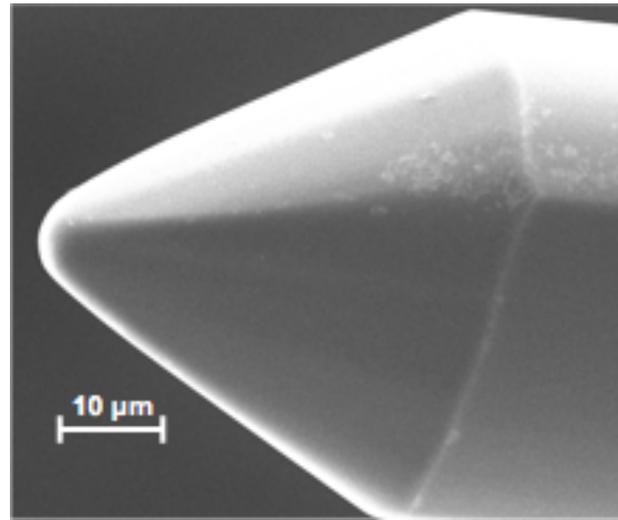
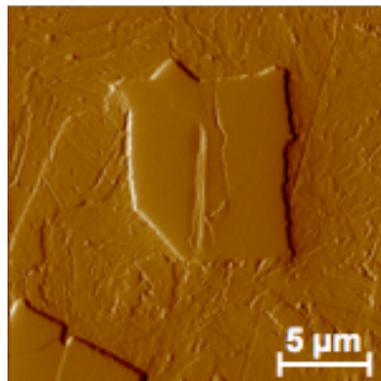
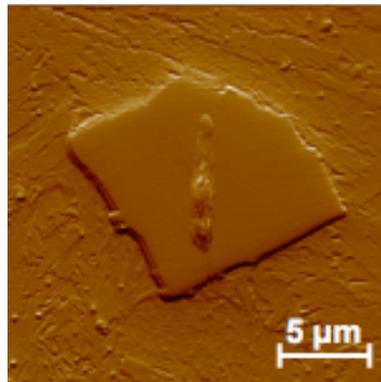
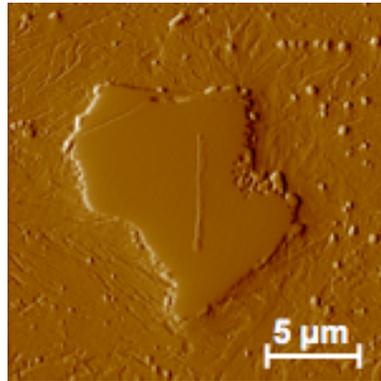
# *Propriedades mecânicas*



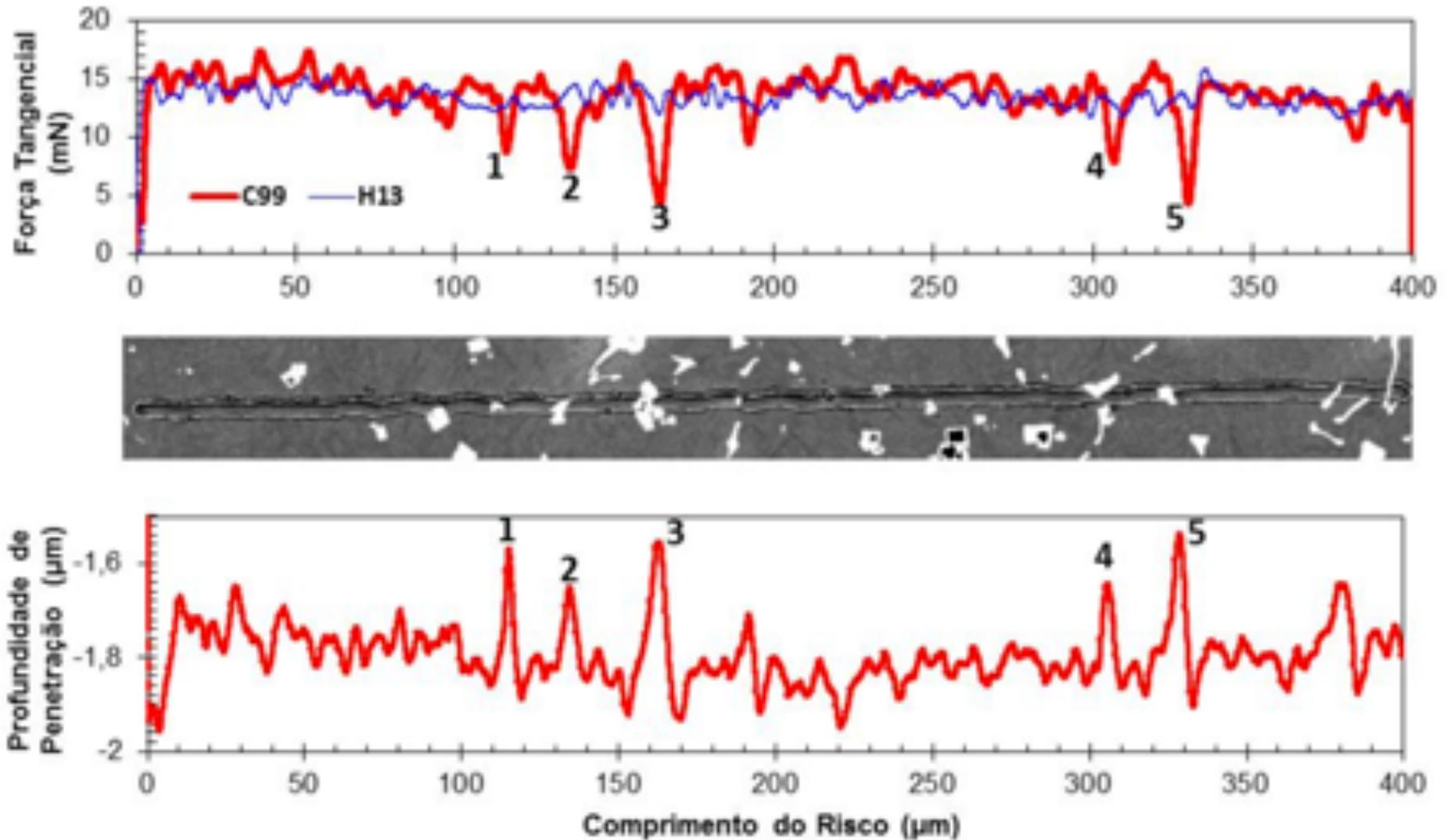


# Cerâmicas avançadas

# Cerâmicas: desgaste e atrito



# Cerâmicas: desgaste e atrito





# ***Cerâmicas: desgaste e atrito***

## ❖ **Métrica de desgaste**

### ❖ **Equação de Archard**

❖ **Q = volume removido**

❖ **W = carga aplicada**

❖ **L = comprimento total de desgaste**

❖ **H = dureza**

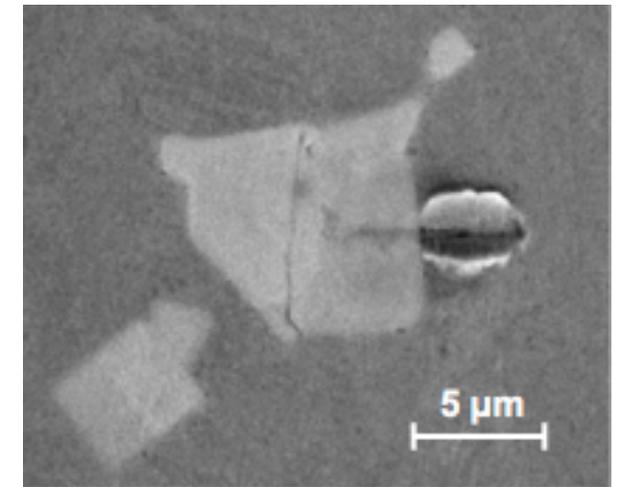
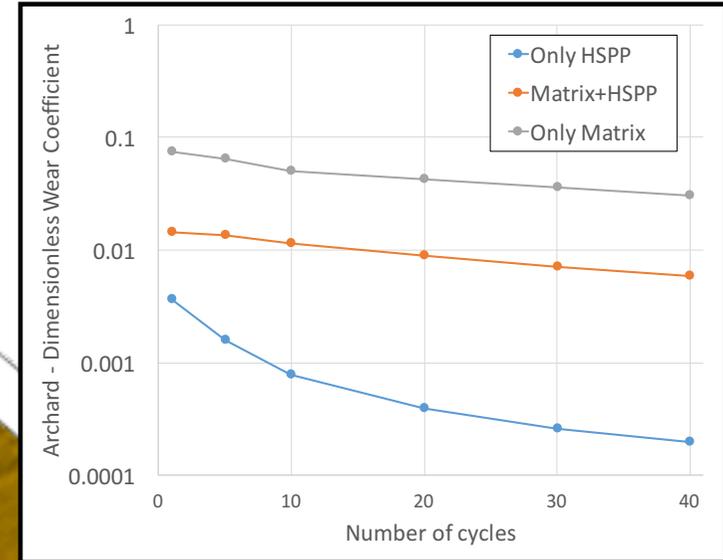
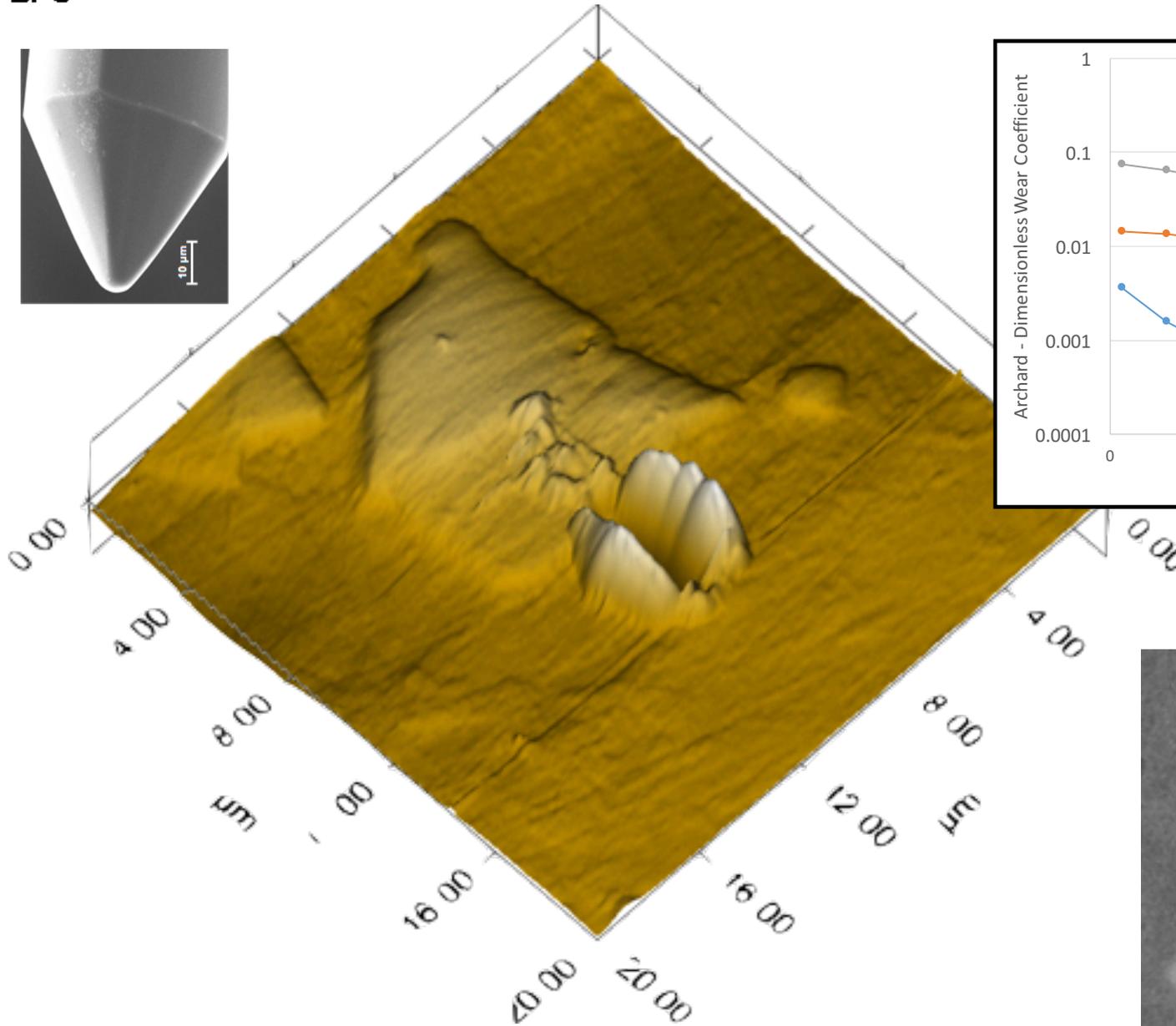
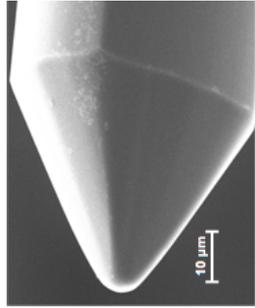
❖ **k = coeficiente de desgaste**

$$Q = \frac{kWL}{H}$$



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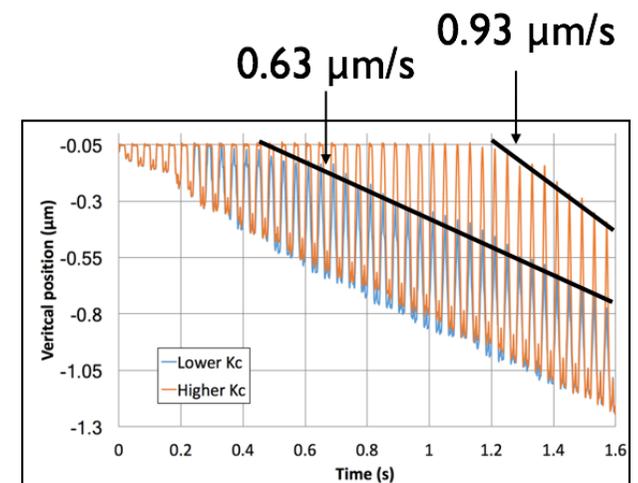
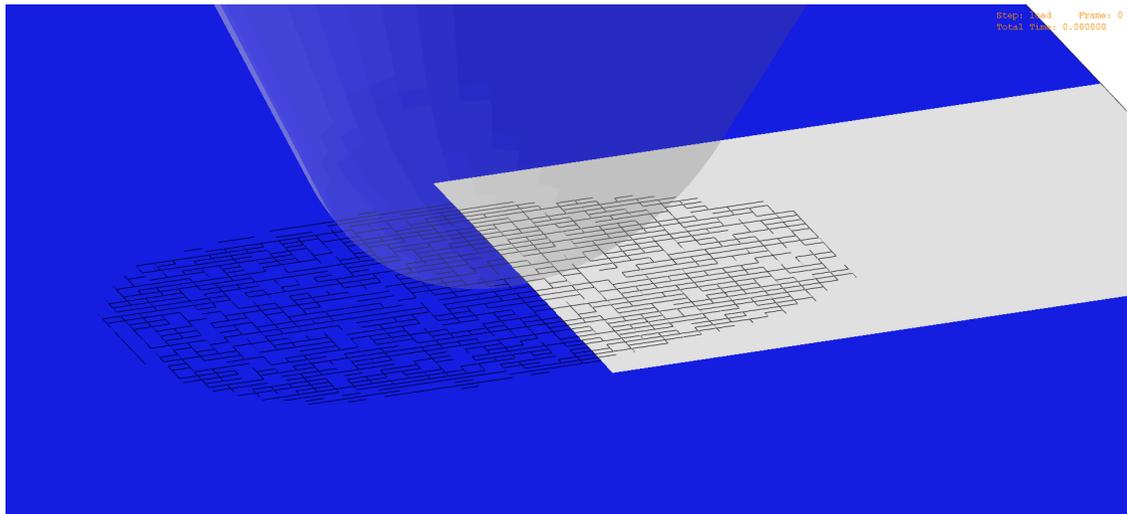
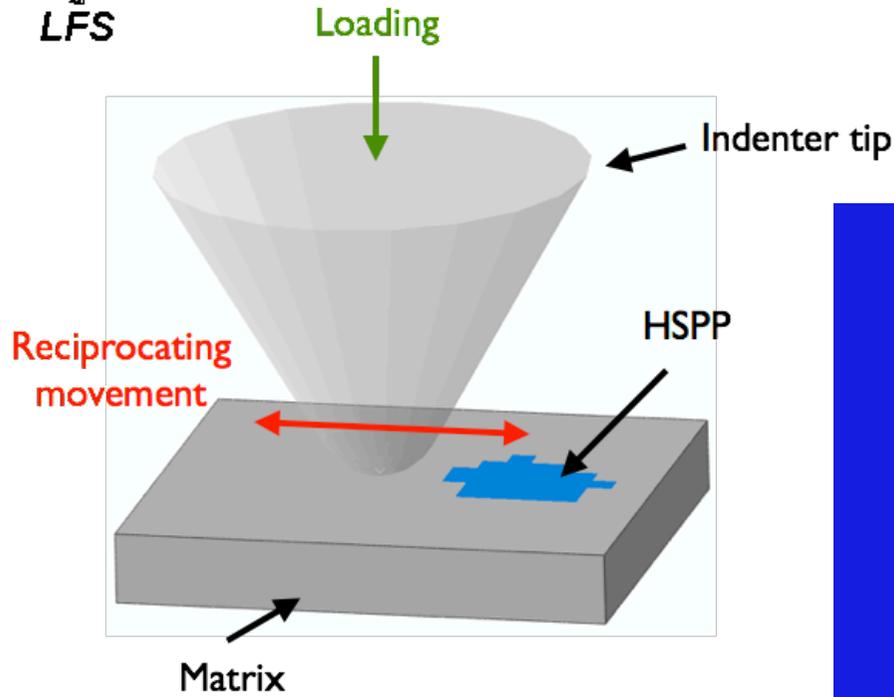
# Cerâmicas: desgaste e atrito



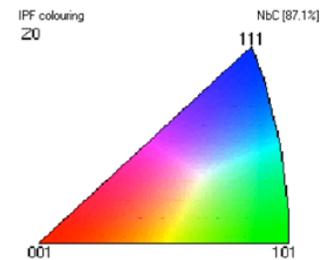
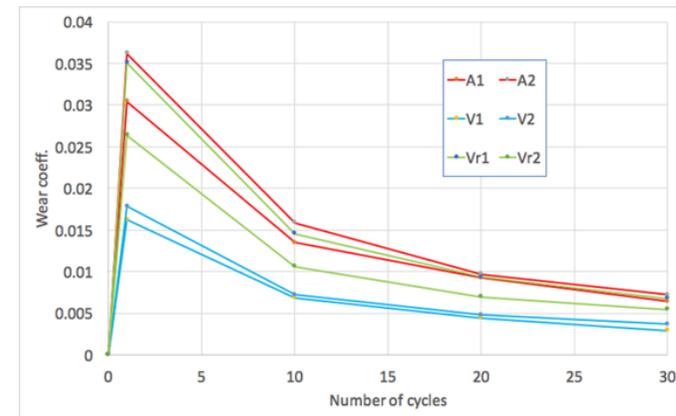
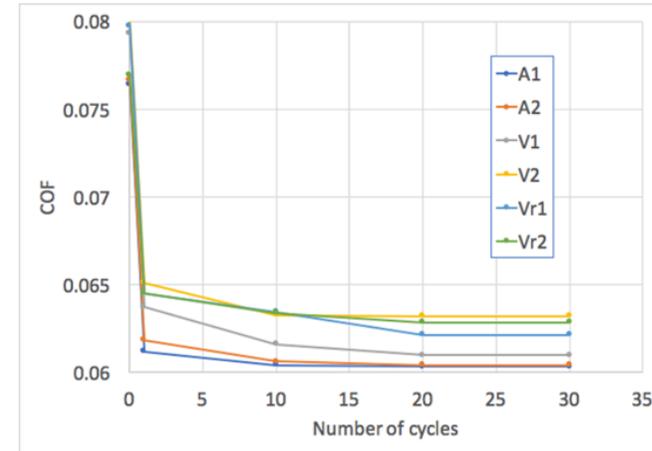
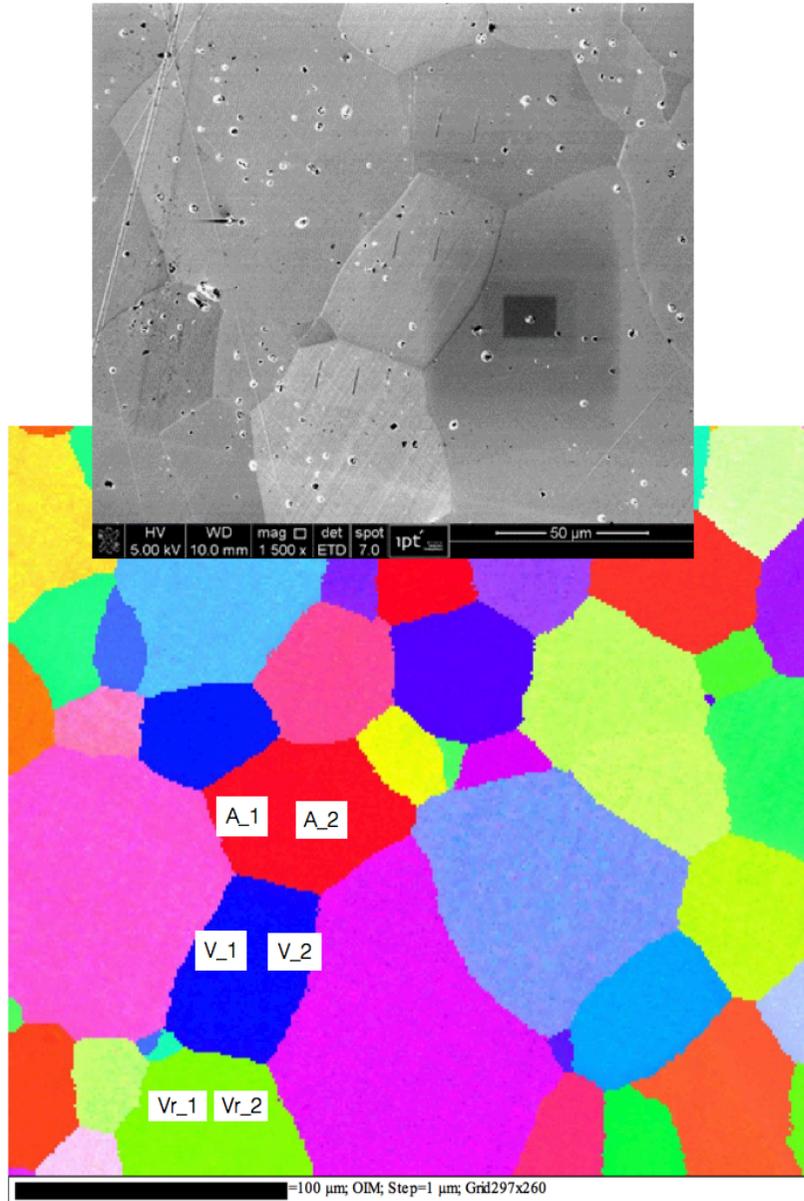


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# Cerâmicas: desgaste e atrito

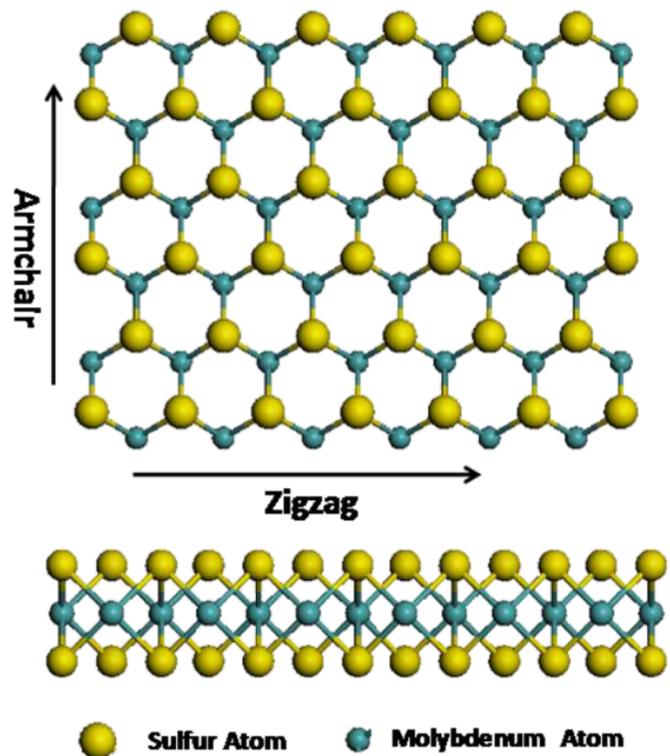


# Cerâmicas: desgaste e atrito

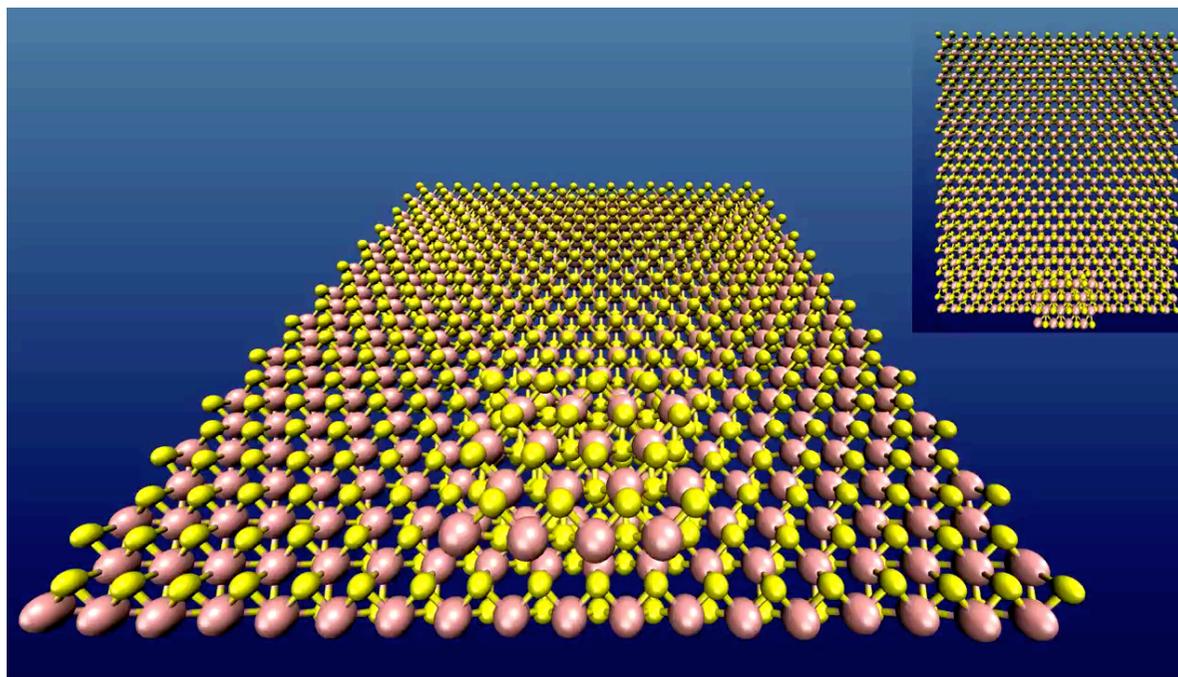




# Cerâmicas: grafeno e bi-sulfeto de molibdênio



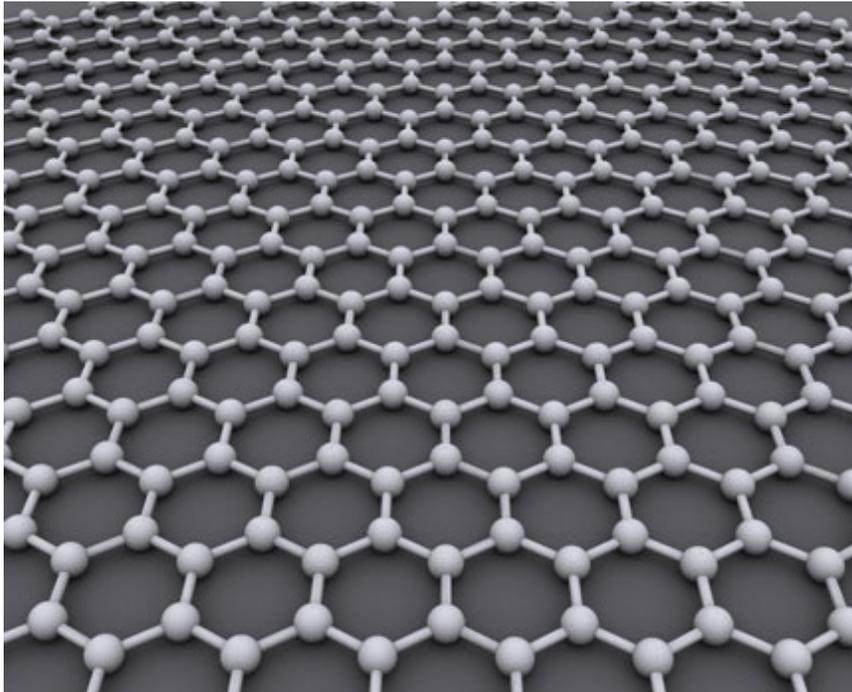
<http://www.beilstein-journals.org/bjnano/articles/7/132>



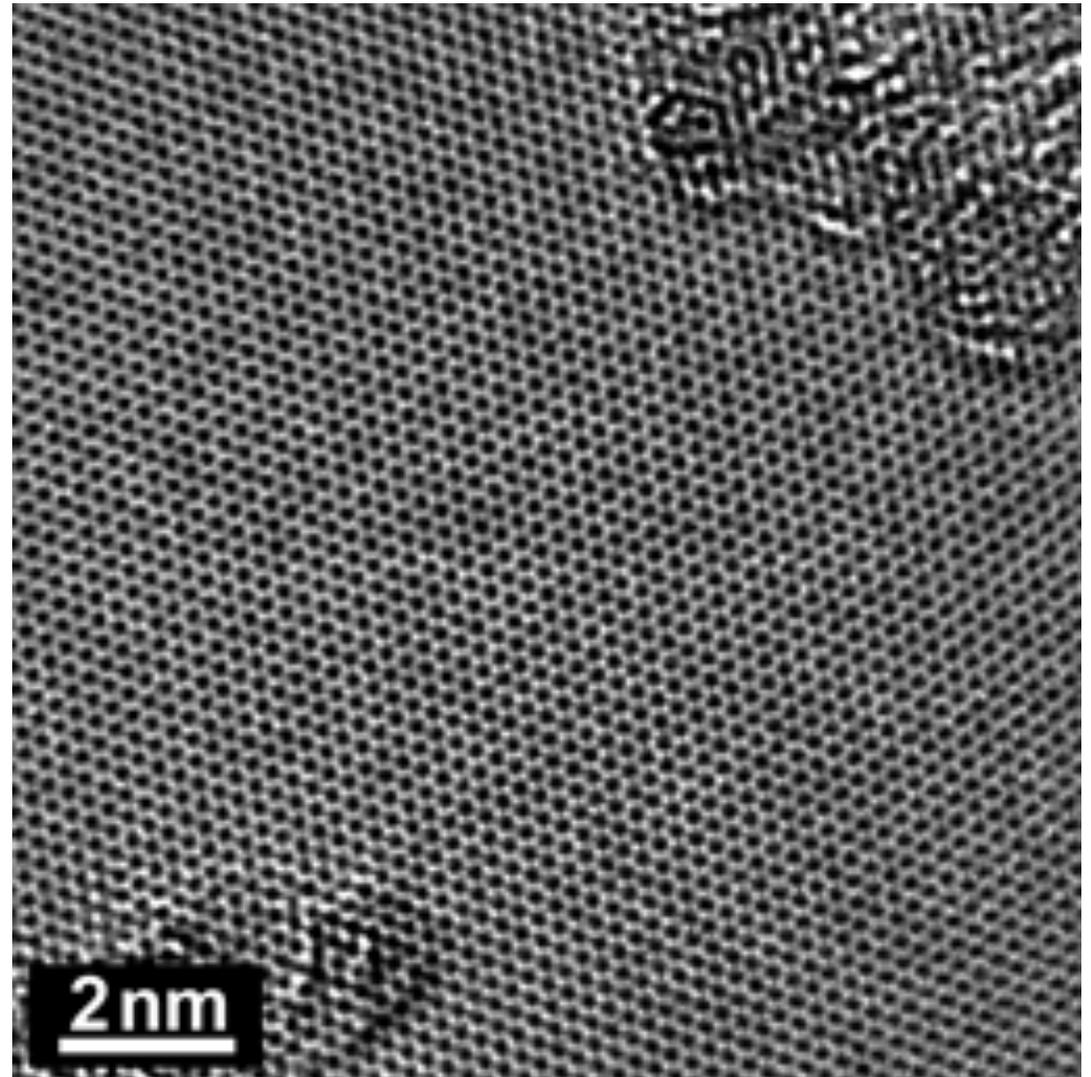
<https://www.youtube.com/watch?v=Fudqa8QbEPg>



# Cerâmicas: grafeno e bi-sulfeto de molibdênio



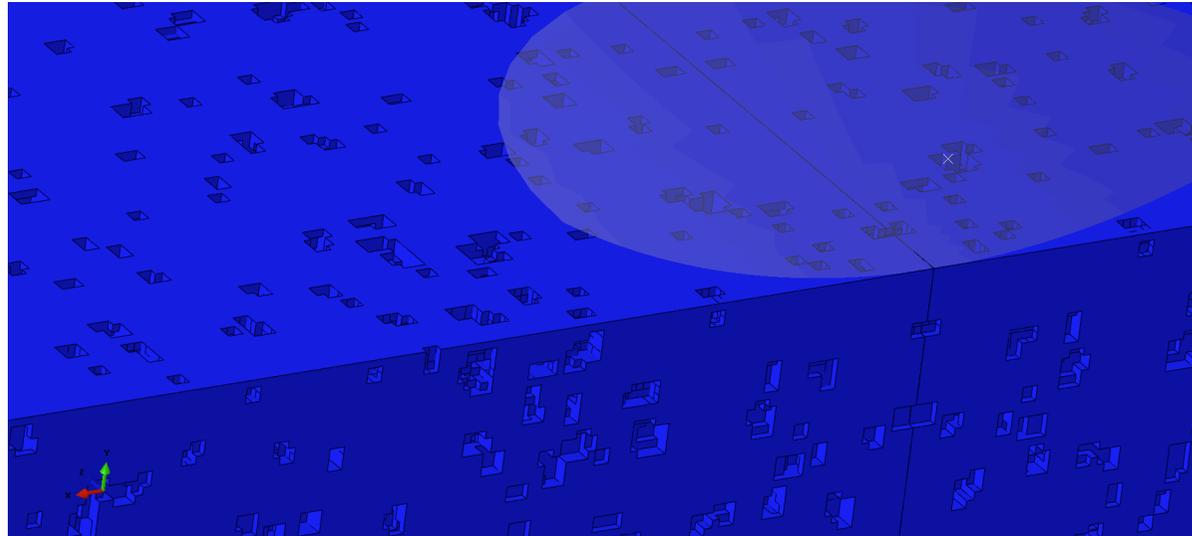
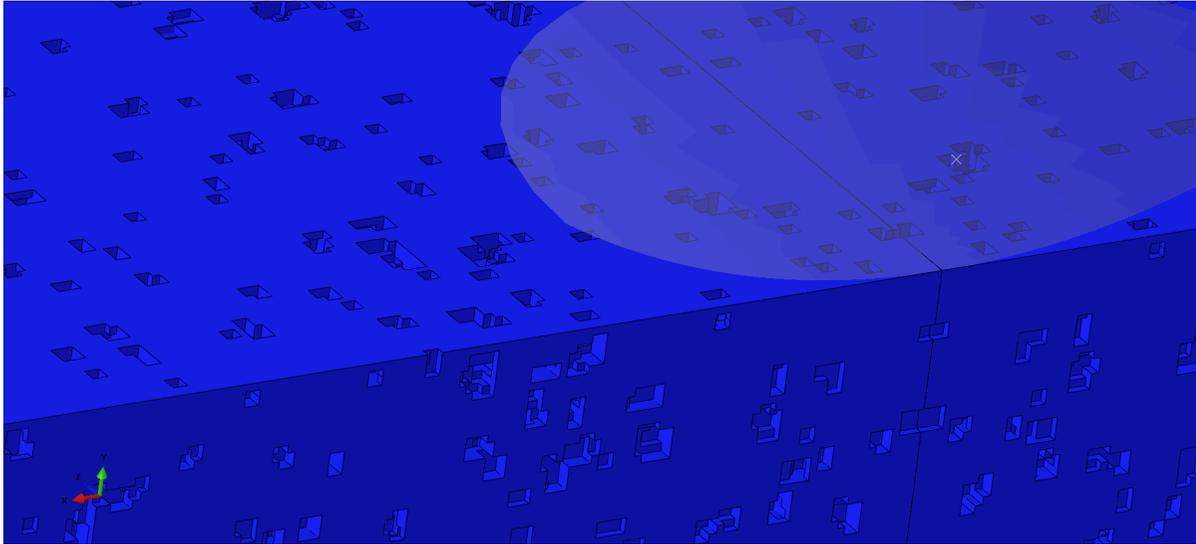
[http://www.tedpella.com/Support\\_Films\\_html/Graphene-TEM-Support-Film.htm#graphene\\_films](http://www.tedpella.com/Support_Films_html/Graphene-TEM-Support-Film.htm#graphene_films)



<http://www.cen.dtu.dk/english/research/projects/actual-high-resolution-tem-on-graphene>



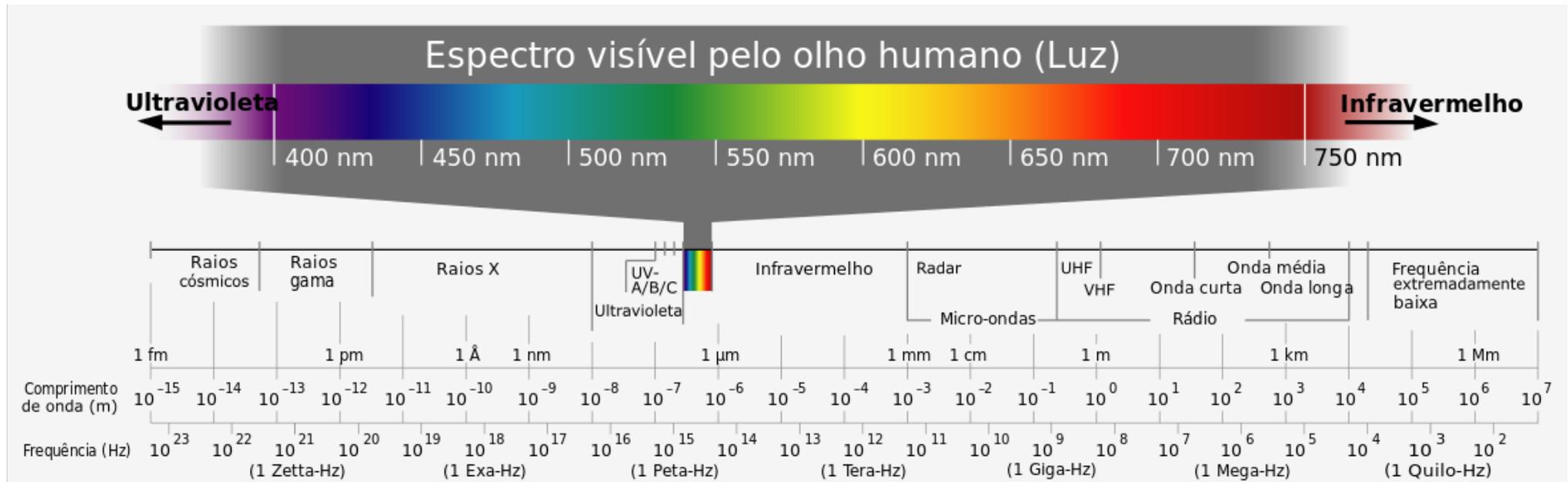
# Cerâmicas: porosidade



# Cerâmicas: ópticas

❖ Transmissão, absorção, emissão, reflexão, dispersão de luz

❖ Faixas de comprimento de onda (UV, Vis, IF, NIF)



<https://commons.wikimedia.org/w/index.php?curid=18122584>

❖ Aplicação: acessos, fibras ópticas

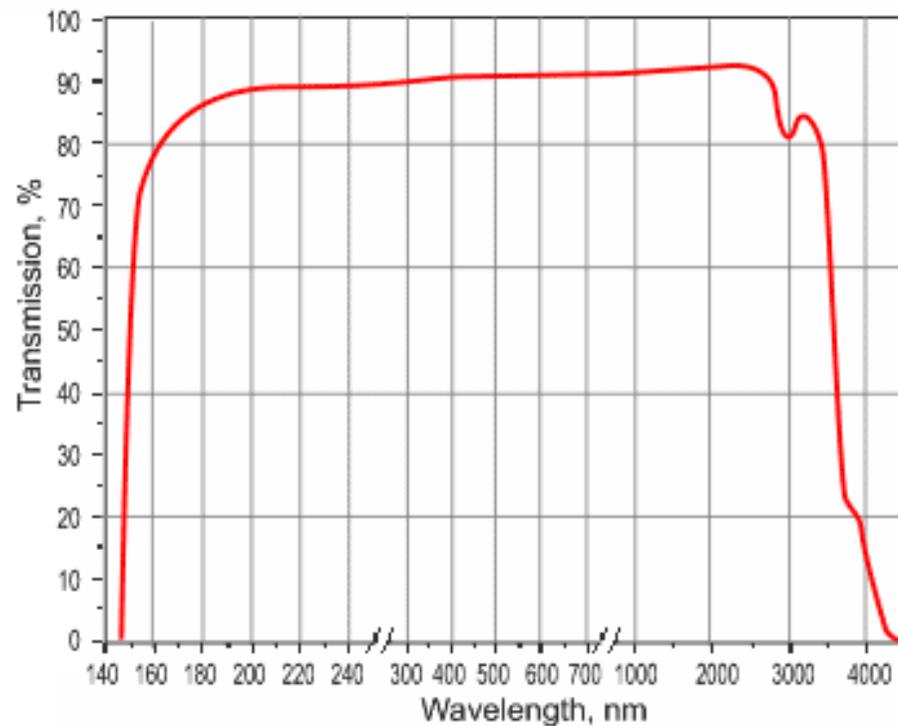


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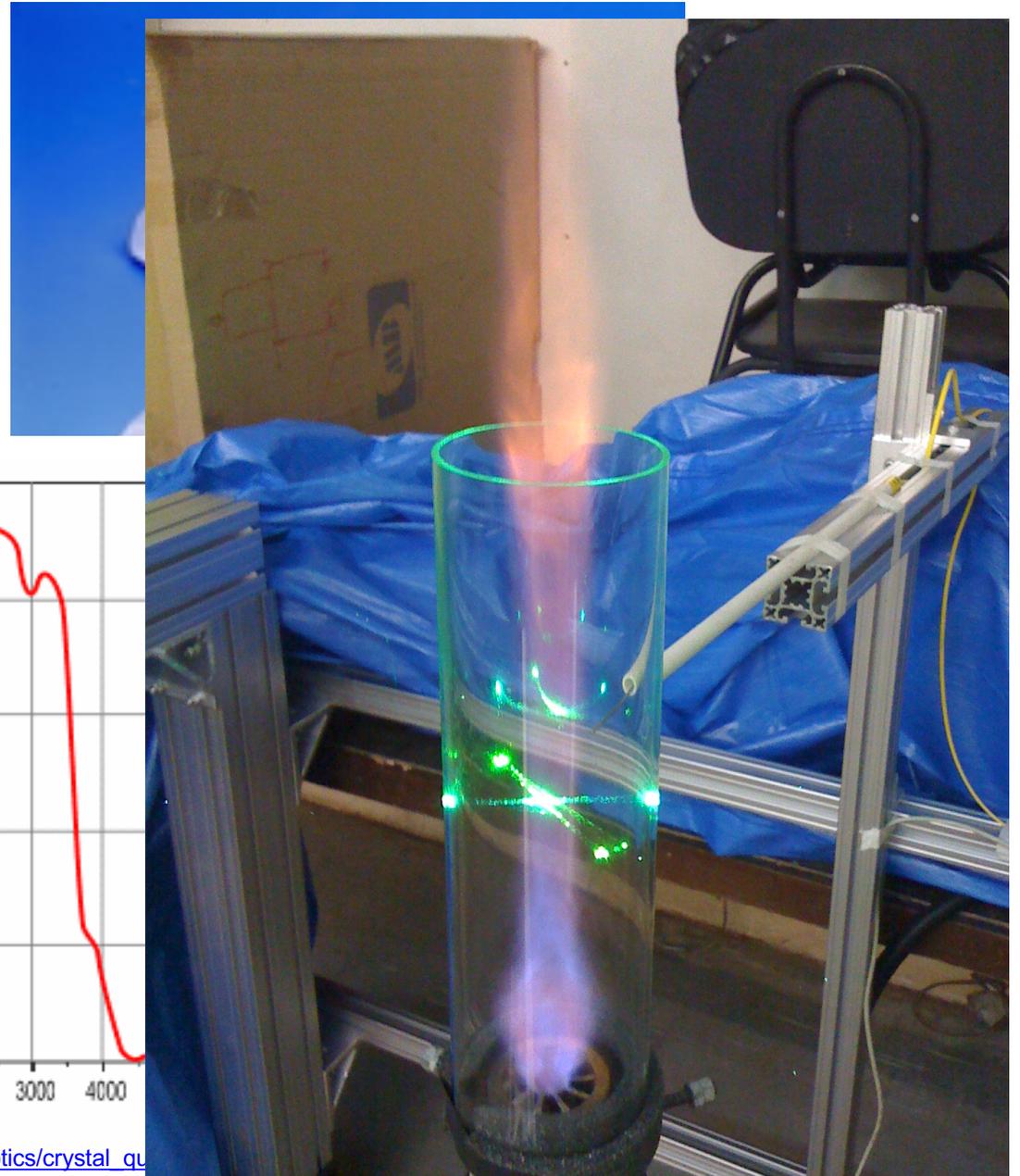
# Cerâmicas: ópticas

## ❖ $\text{SiO}_2$ fundido - Quartzo

- ❖  $T_f - 1500^\circ \text{C}$
- ❖  $H - 8.8 \text{ GPa}$
- ❖  $E - 71.7 \text{ GPa}$
- ❖  $K_c \sim 1 \text{ MPm}^{1/2}$



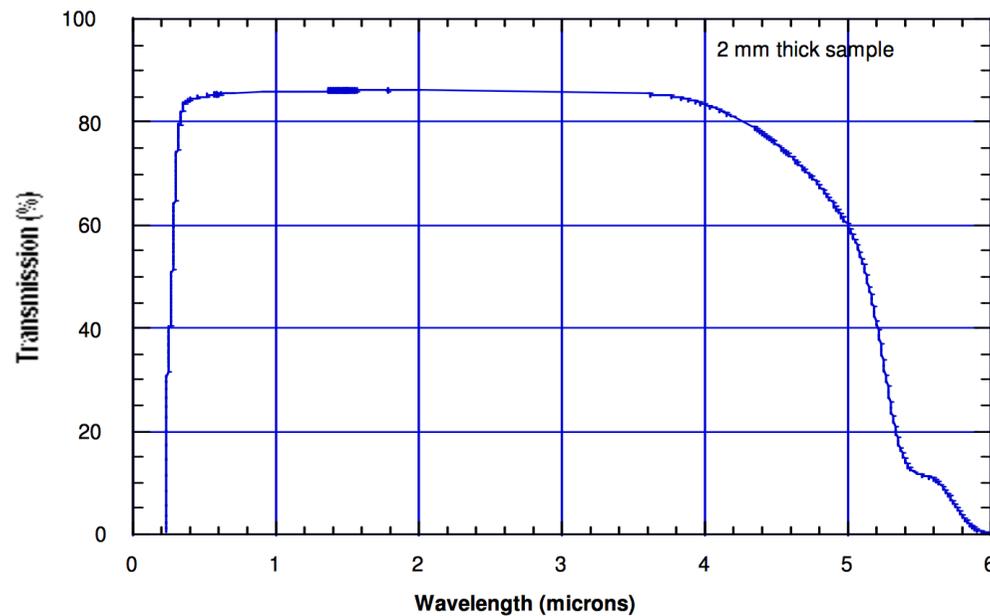
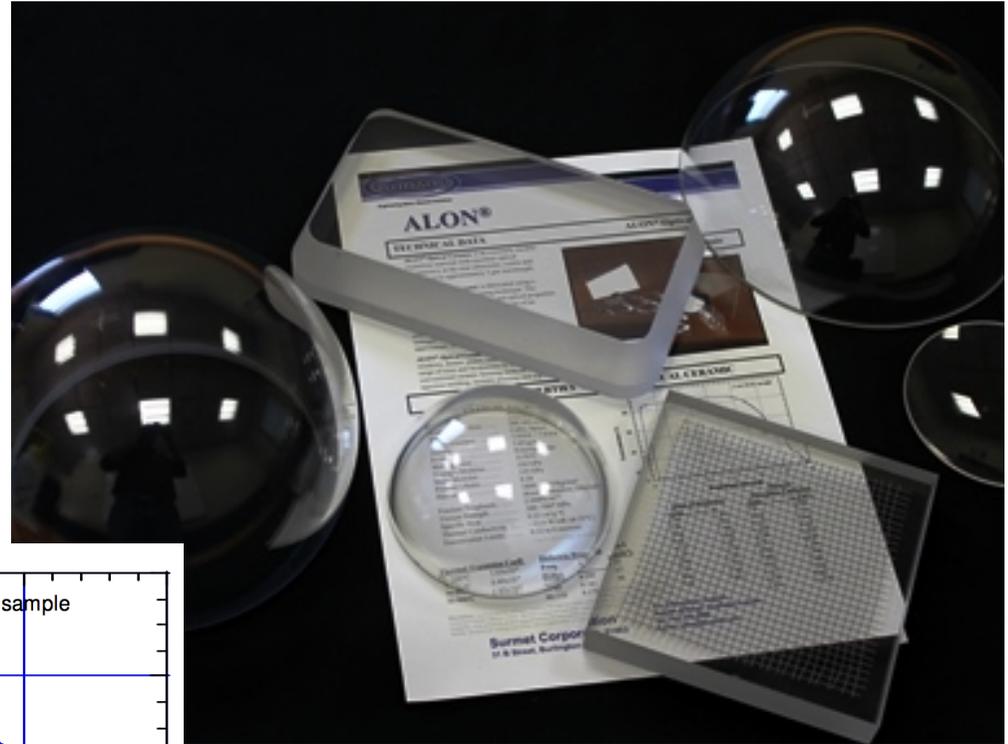
[http://www.tydexoptics.com/materials1/for\\_transmission\\_optics/crystal\\_quartz](http://www.tydexoptics.com/materials1/for_transmission_optics/crystal_quartz)





# Cerâmicas: ópticas

- ❖  $\text{Al}_x\text{O}_y\text{N}_z$  – sinterizado ALON<sup>®</sup>
  - ❖  $T_f$  – 2150° C
  - ❖  $H$  ~ 18 GPa
  - ❖  $E$  – 323 GPa
  - ❖  $K_{IC}$  ~ 2,5  $\text{MPm}^{1/2}$

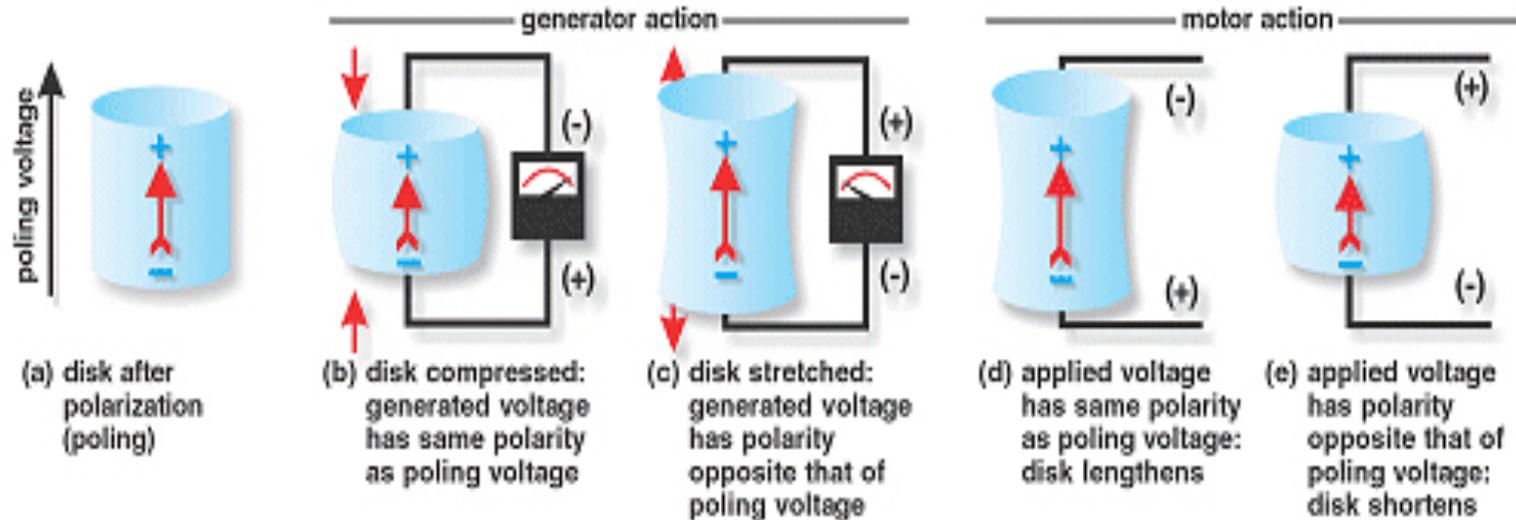


<http://www.surmet.com/technology/alon-optical-ceramics/>

# Cerâmicas: eletro-mecânica

- ❖ **Efeito direto:** diferença de potencial elétrico quando aplicada uma deformação mecânica
- ❖ **Efeito inverso:** deformação mecânica quando uma carga elétrica é aplicada

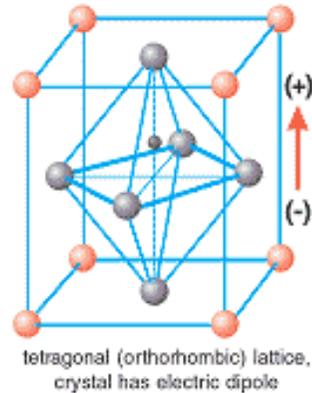
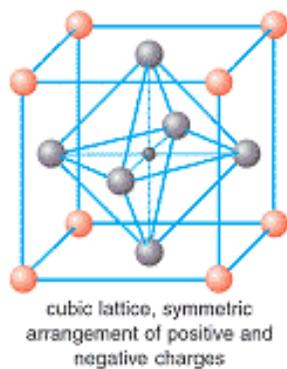
**Figure 1.4** Generator and motor actions of a piezoelectric element



<https://www.americanpiezo.com/knowledge-center/piezo-theory/piezoelectricity.html>

# Cerâmicas: eletro-mecânica

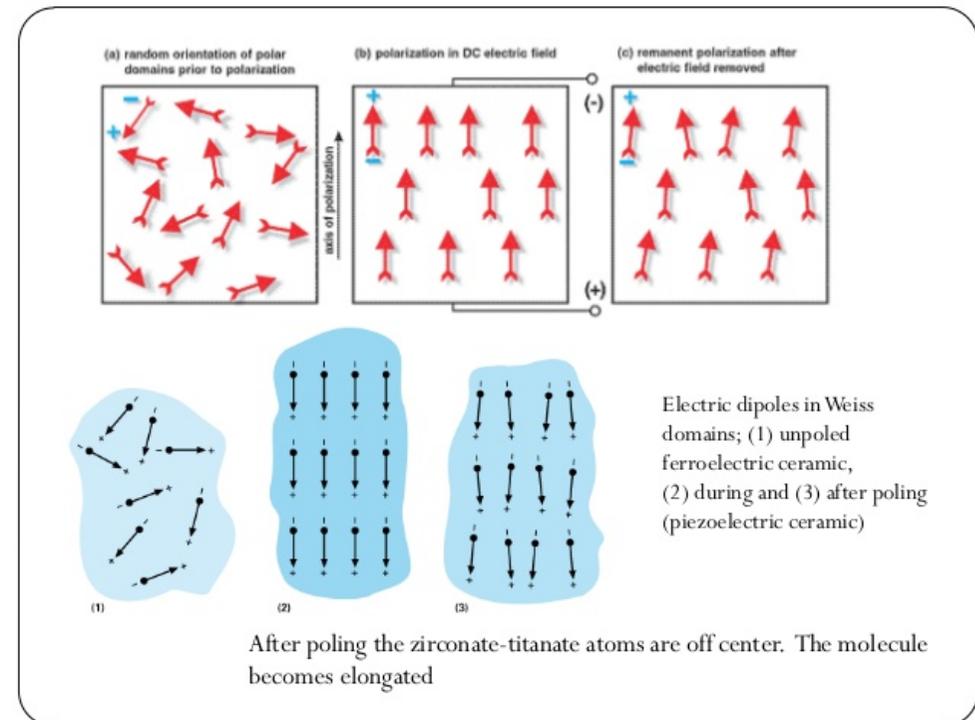
## ❖ Estrutura cristalina: peroviskita



<https://www.americanpiezo.com/knowledge-center/piezo-theory/piezoelectricity.html>

  $A^{2+}$  = Pb, Ba, other large, divalent metal ion  
  $O^{2-}$  = oxygen  
  $B^{4+}$  = Ti, Zr, other smaller, tetravalent metal ion

- ❖ Quartzo ( $SiO_2$ )
- ❖ Titanato de Bário ( $BaTiO_3$ )
- ❖ Titanato zirconato de chumbo (PZT)
- ❖ PLZT (PZT dopado com La)

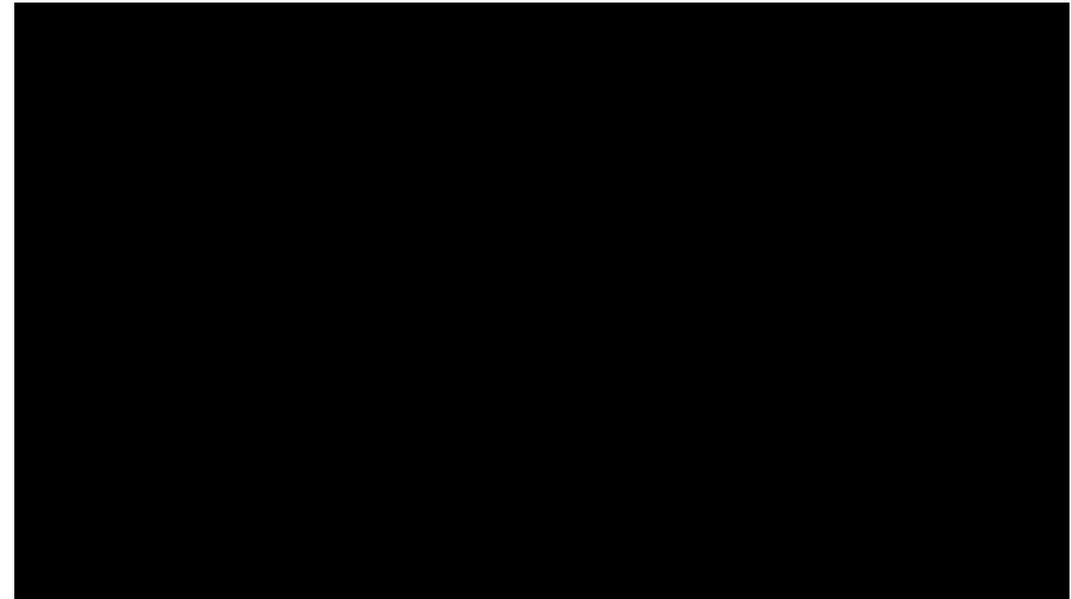




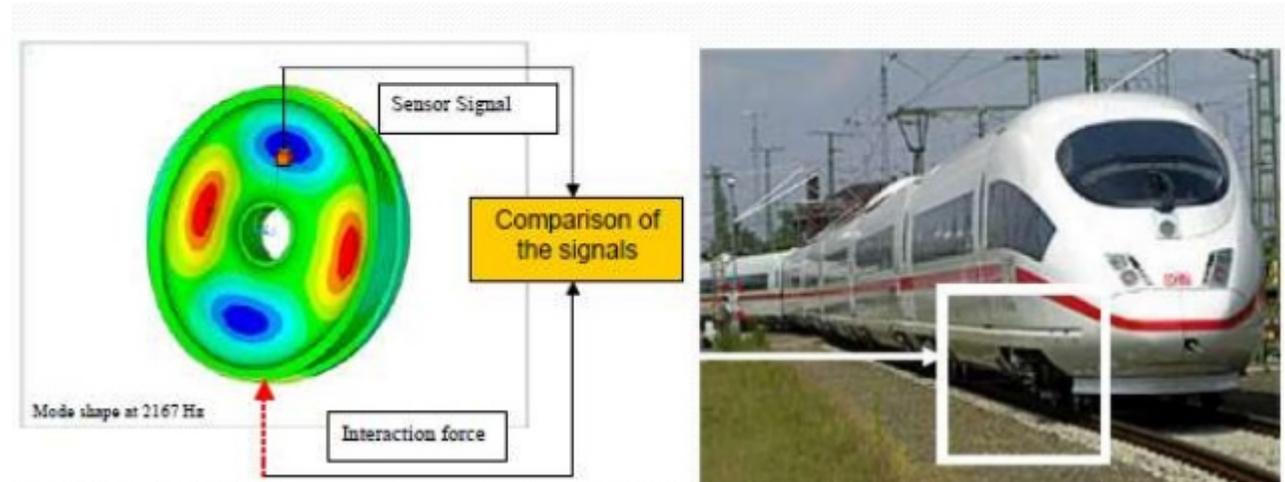
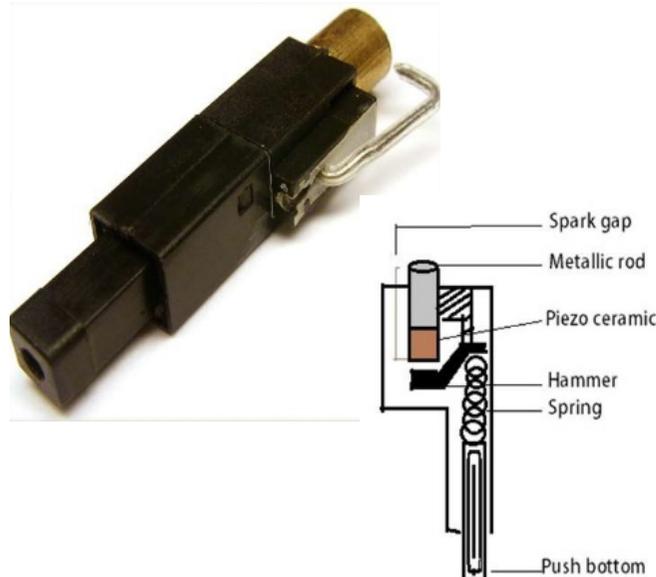
# Cerâmicas: eletro-mecânica

## ❖ Aplicação

- ❖ Relógio – Quartzo oscilador
- ❖ Sensor de deformação ou vibração – PZT
- ❖ Transdutor – PZT
- ❖ MEMS, Acendedores



<https://www.youtube.com/watch?v=sPxnpYHQyFg>



<https://pt.slideshare.net/SubhraShankhaBhattac/piezoelectric-sensors-brief-discussion>