

TRIBOLOGIA DE ELEMENTOS DE MÁQUINAS: ABORDAGENS EXPERIMENTAL E NUMÉRICA

09 de Setembro de 2015, Vitória/ES

Carlos Henrique da Silva (LASC)

AGENDA:

❑ Laboratório de Tribologia

- Giuseppe Pintaúde
- Julio Klein das Neves
- Carlos H. da Silva

- João L. do Vale
(UTFPR/Londrina)

❑ Laboratório de Análise Numérica

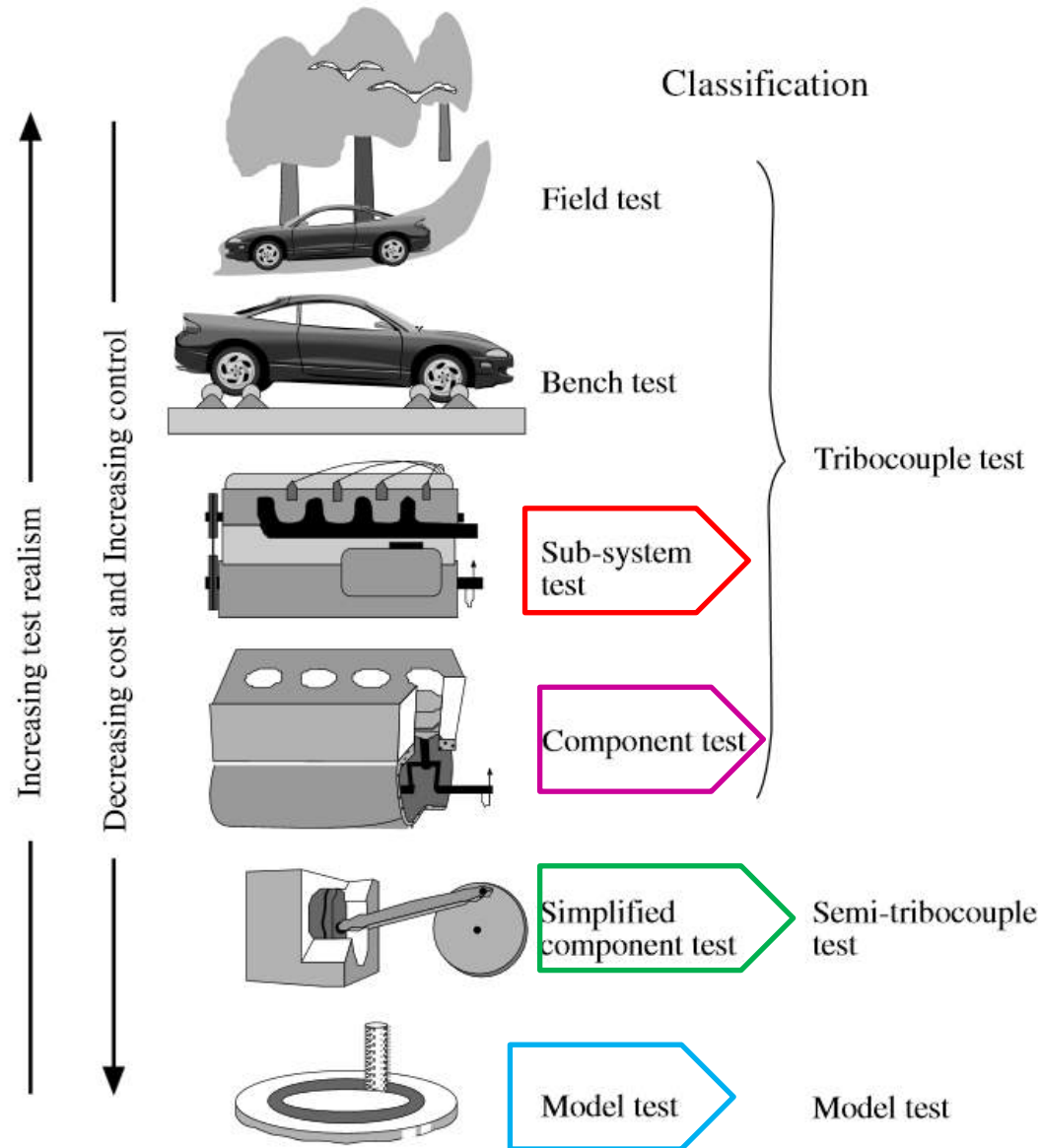
- Marco Antonio Luersen

- Ana Paula Carvalho da Silva Ferreira



Laboratório de Mecânica Estrutural

Grau de realismo x Transferência (tribotestes)



- Engrenagens
 - Mancal de Deslizamento
 - Pistão/Camisa/Anel
- Ferro Fundido Nodular (TUPY)
 - Austempera / Tempera
 - Aços Liga (Têmpera / Cementação)
 - Ensaio tipo FZG
 - Quantificação dos danos
 - Análise de Imagem
 - Análise de Tensões
 - Contato
 - Flexão
 - Mecânica da Fratura
 - Tenacidade a fratura (K_{IIc})
 - Propagação de trincas

- Engrenagens

- Mancal de Deslizamento

- Pistão/Camisa/Anel



- Pistão – Cilindro

- Bomba de Injeção Diesel

- Desgaste x Análise Numérica

- Anel - Camisa

- *Motor de Combustão*

- *Folded Metal*

- Ferro Fundido

- Vermicular x Cinzento

- Anel - Camisa

- *Motor de Combustão Monocilindro*

- *EGR*

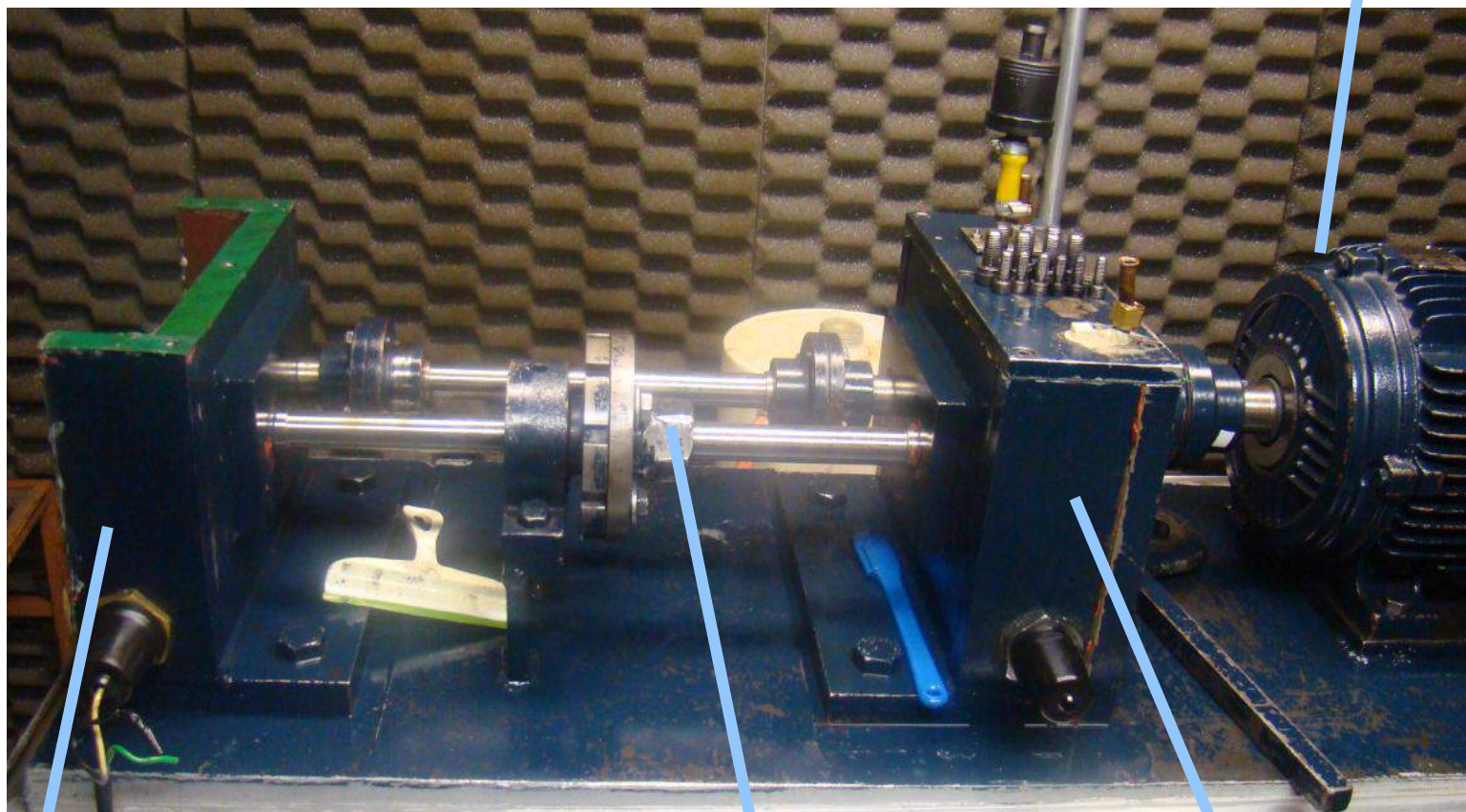
- Análise do óleo



- Ensaios padronizados por norma
 - Estudo do lubrificante
- Ensaios não-normalizados
 - Estudo do comportamento das engrenagens
 - Material
 - Acabamento Superficial
 - Geometria
 - Tratamento Superficial

- Vista Lateral

Motor Elétrico (10 kW)



Caixa de Ensaio

Eixo de aplicação de torque

Caixa Motor

Sensor de temperatura - TIC



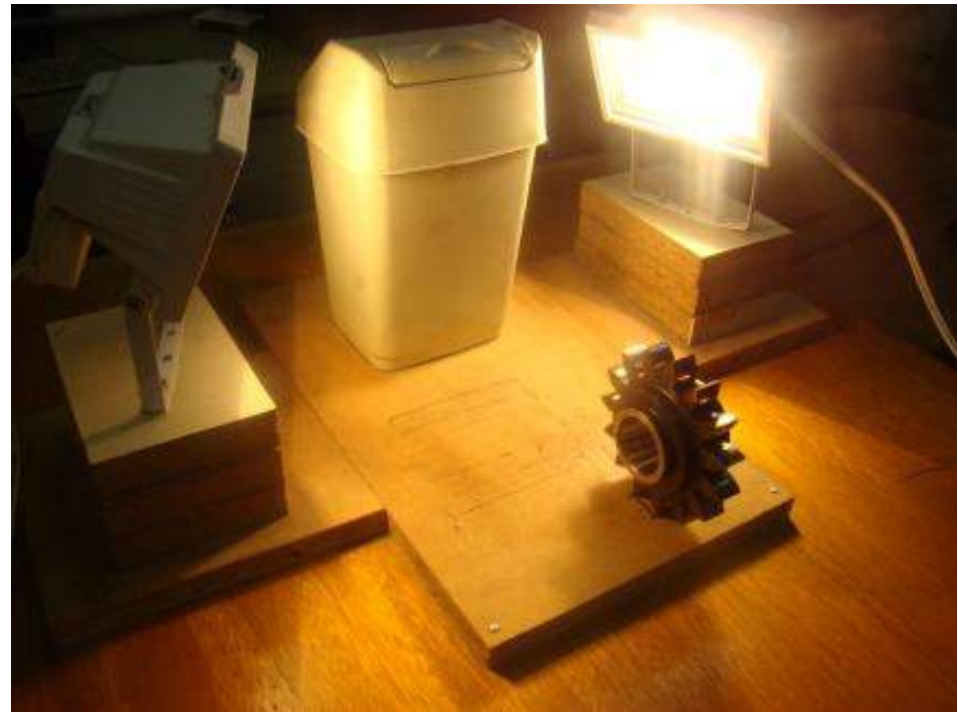
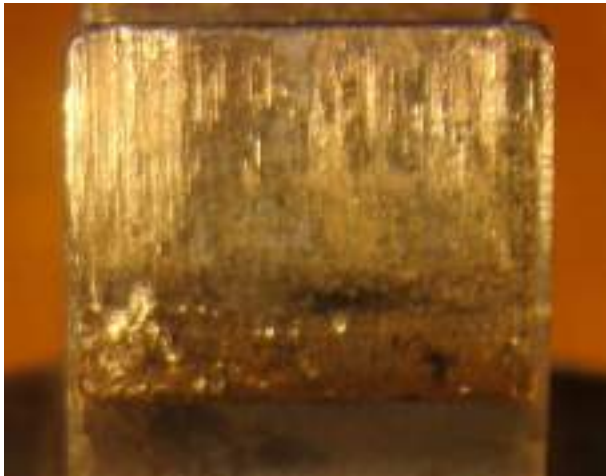
Caixa de ensaio

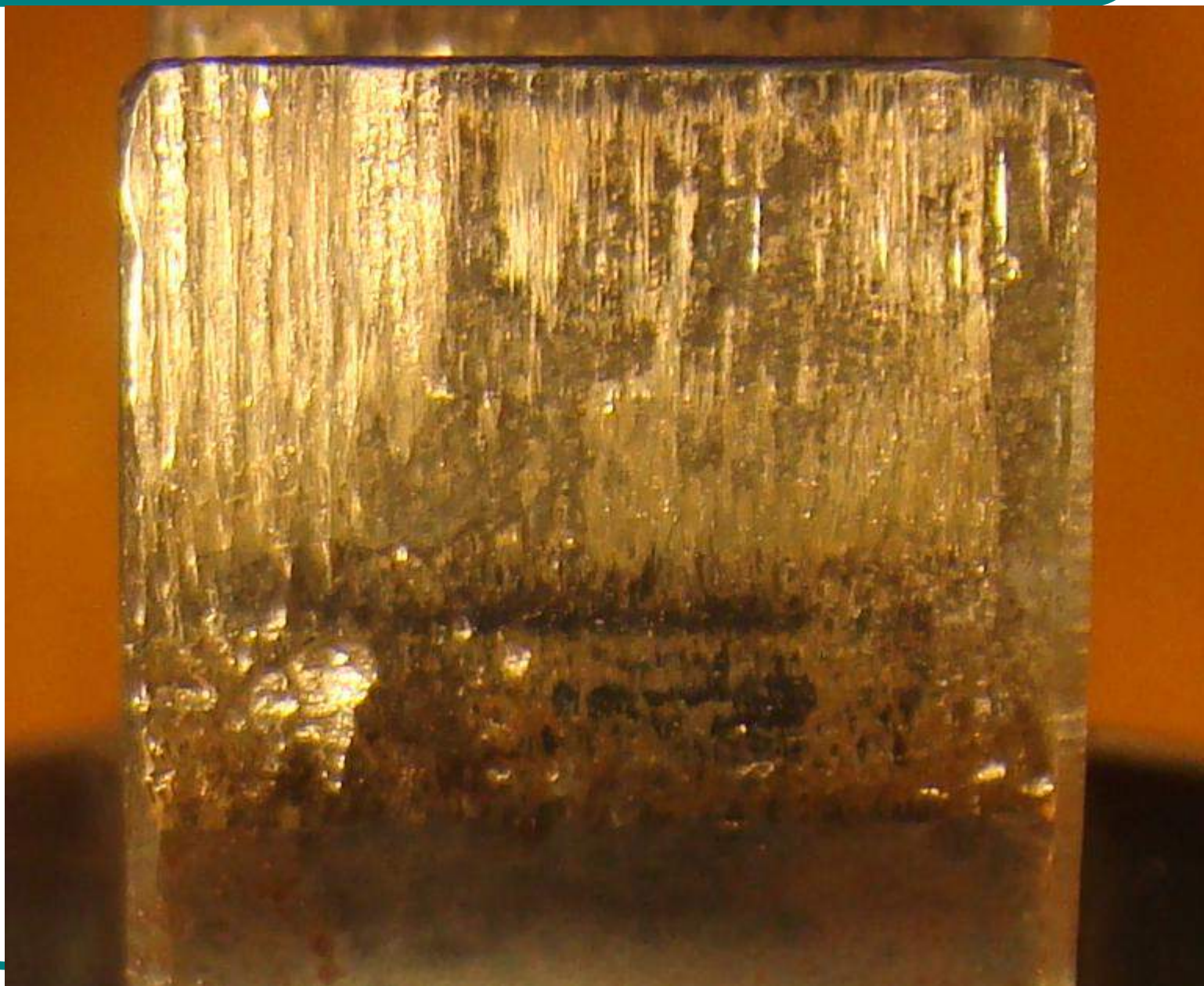
Resistência elétrica

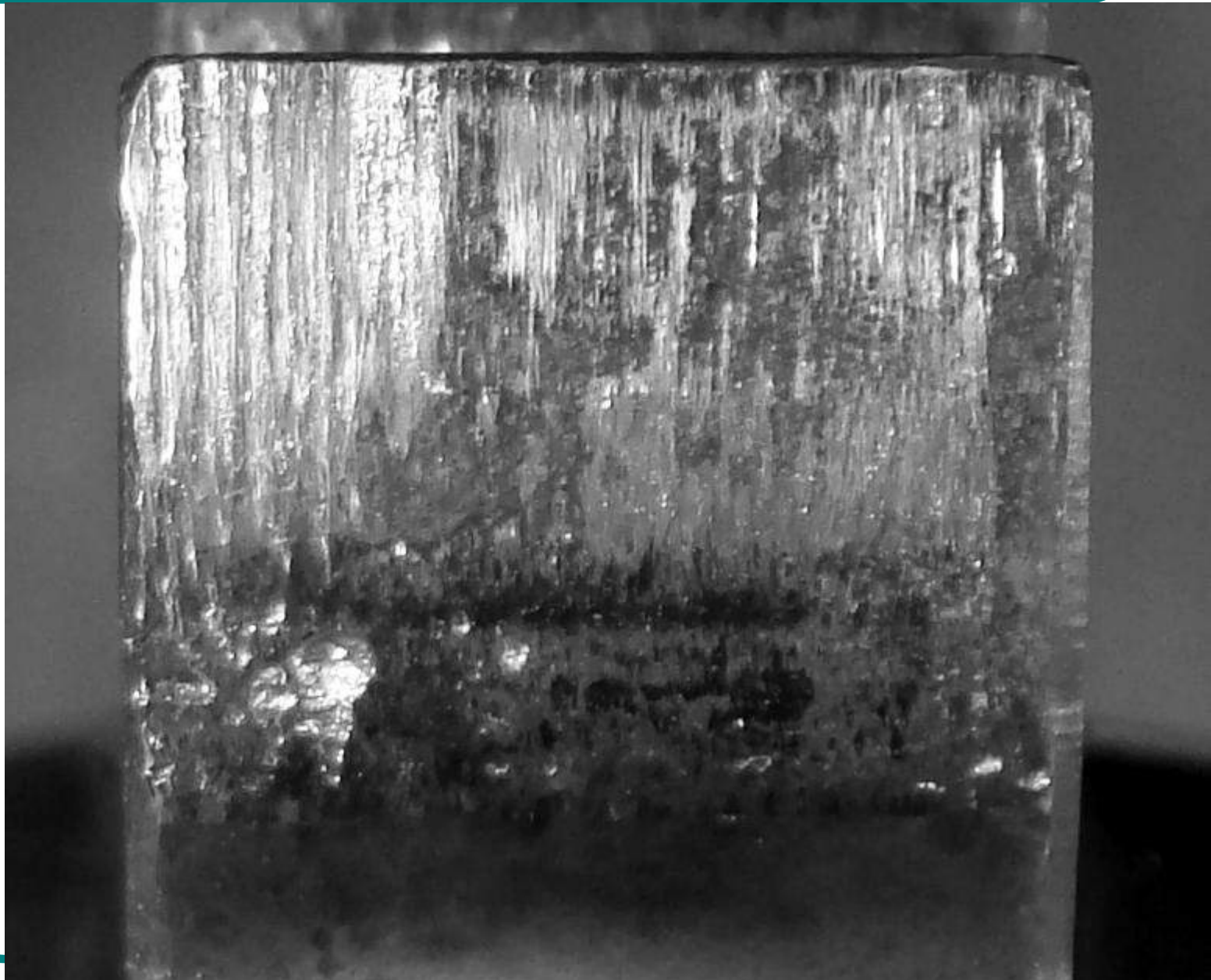
Fotografia da superfície de desgaste

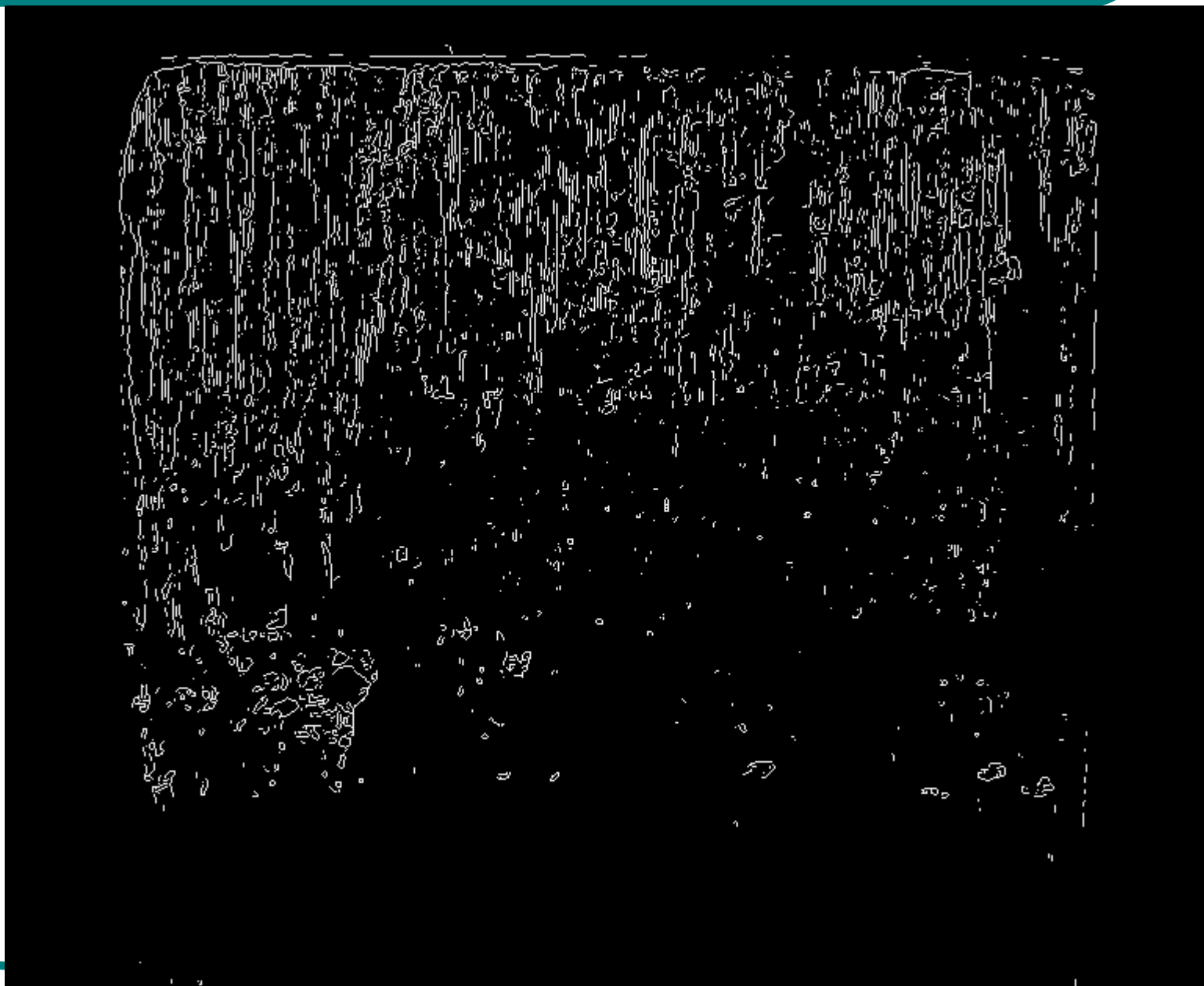
BANCADA PARA AQUISIÇÃO DE IMAGENS DO FLANCO DOS DENTES

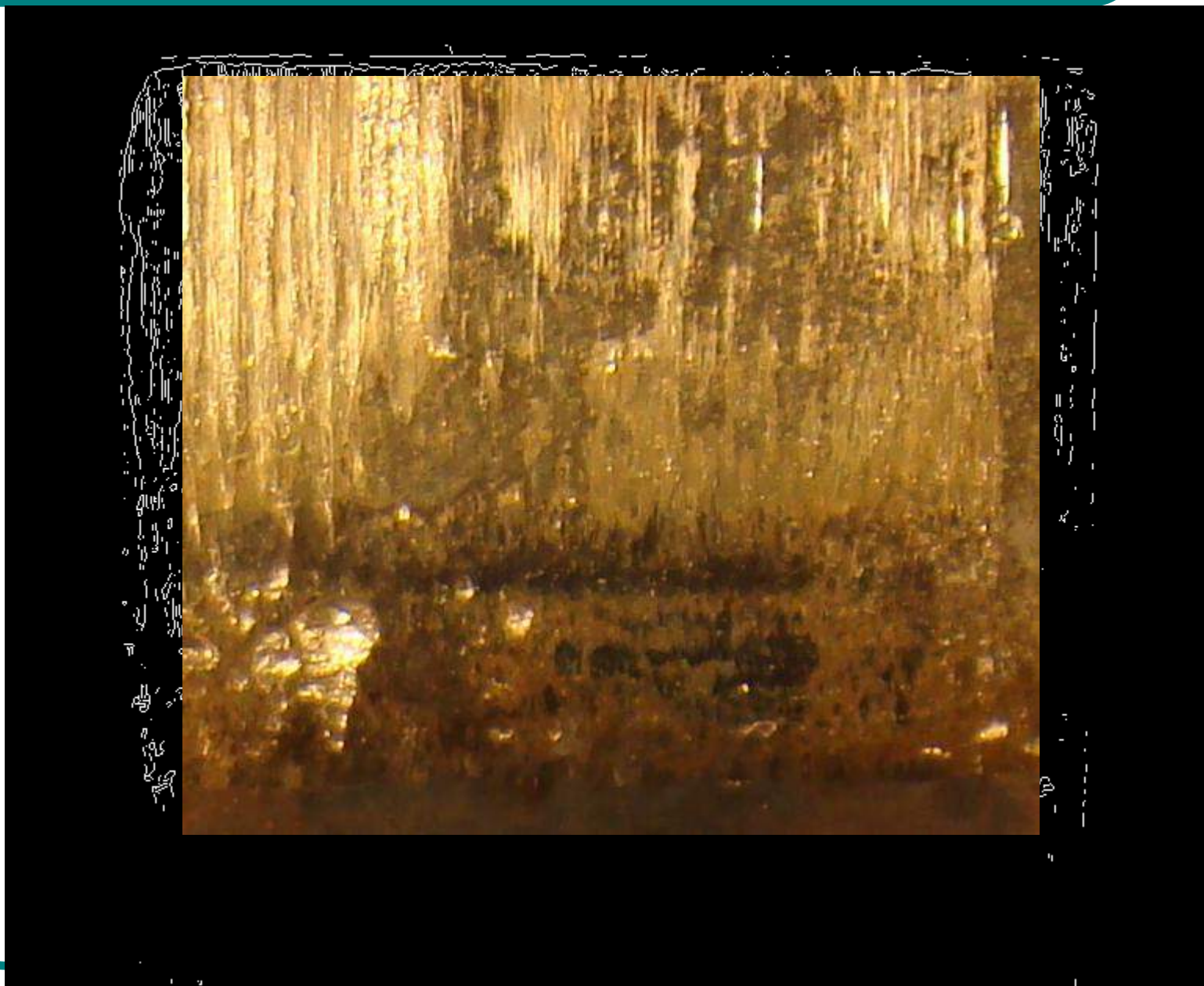
- Iluminação e distância focal constantes
- Máquina fotográfica da marca SONY modelo DSC-H9
 - 8,1 megapixels + *zoom* máximo de 8,5 x
- *Software* para análise de imagem (Rotina MATLAB) Prof. João Luiz do Vale, MSc.



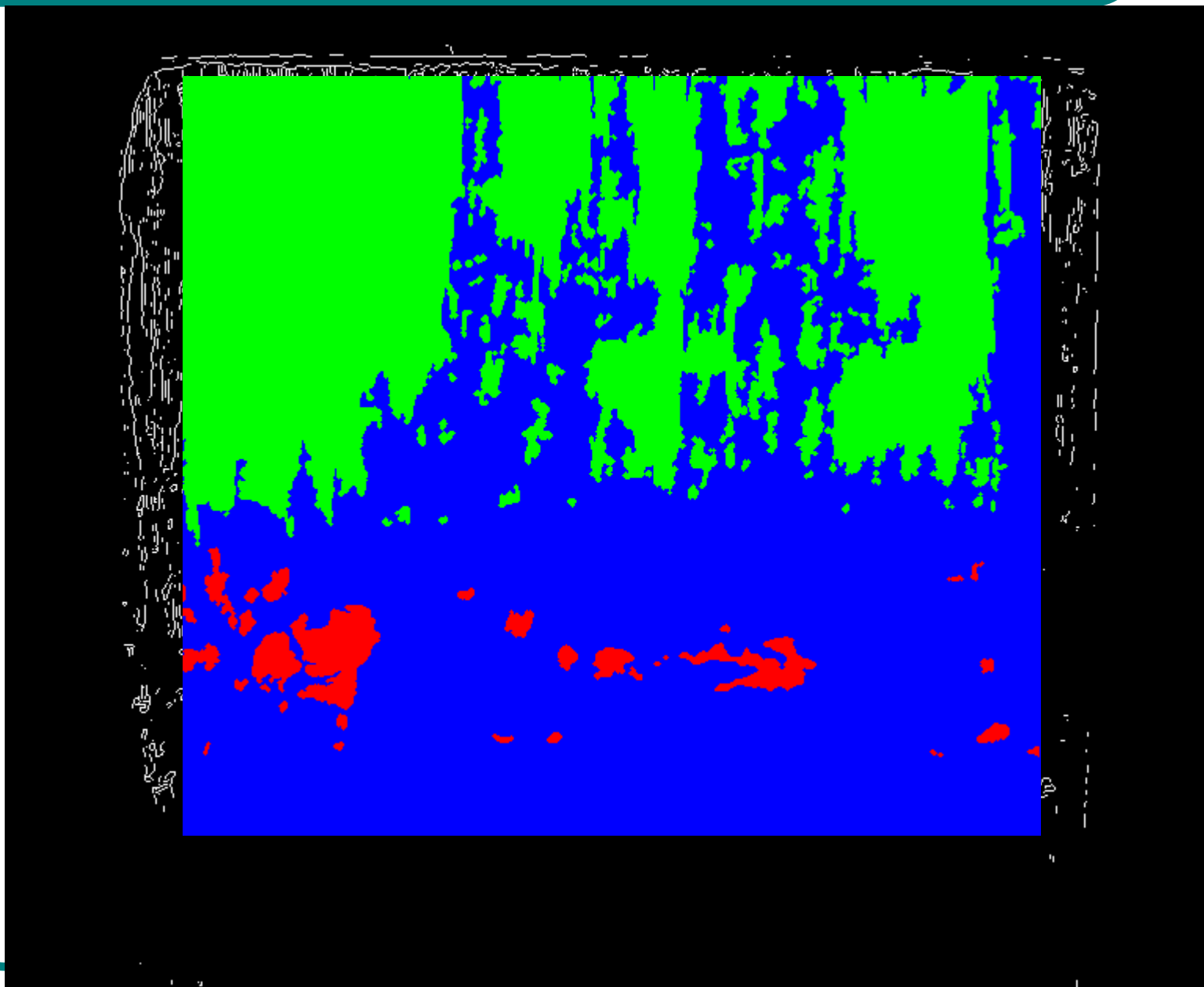


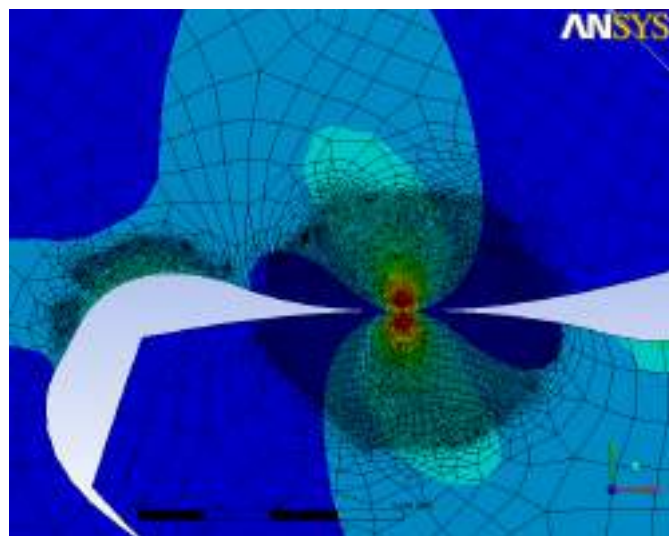
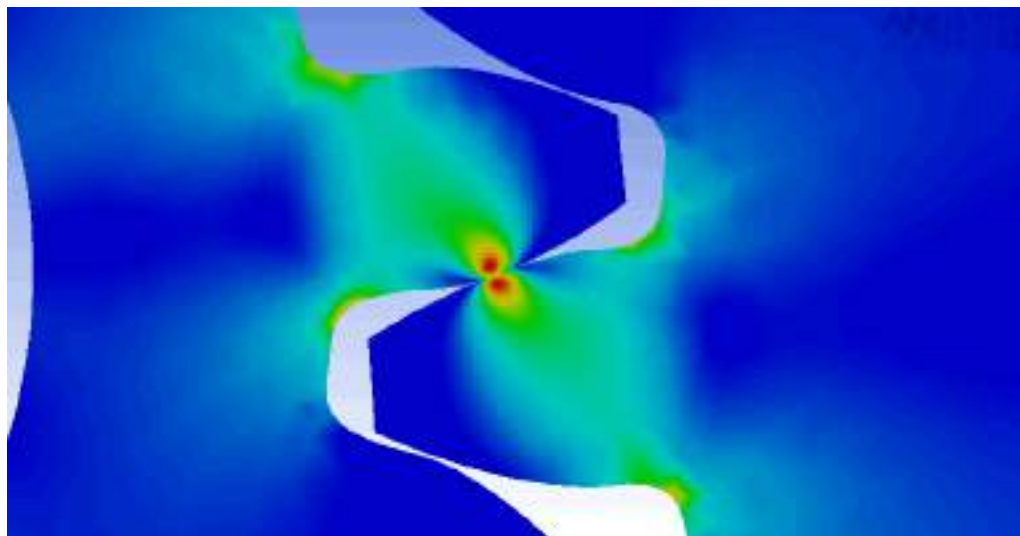




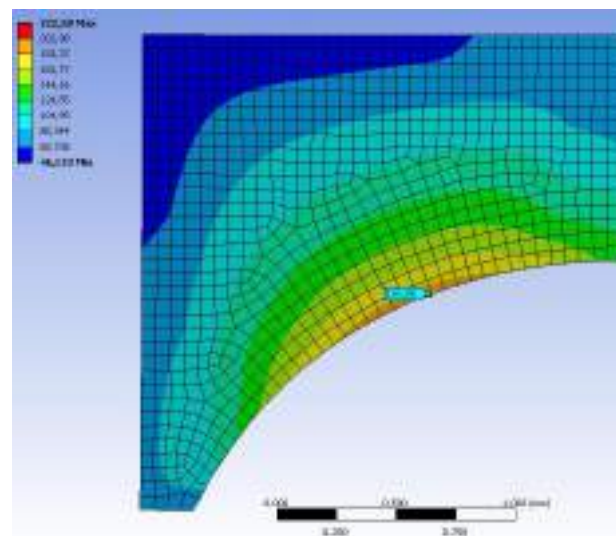






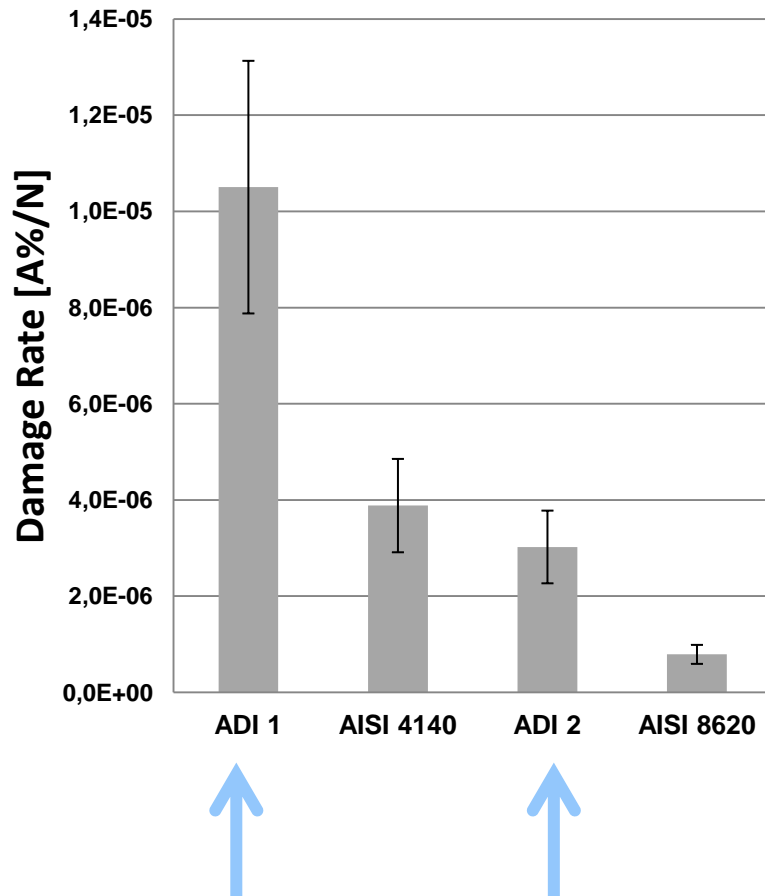


Tensões de Contato

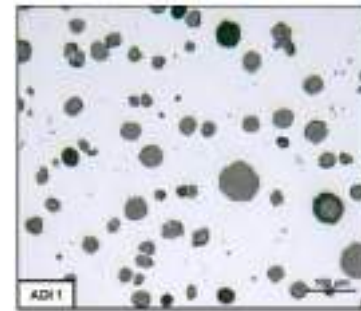


Tensões de Flexão

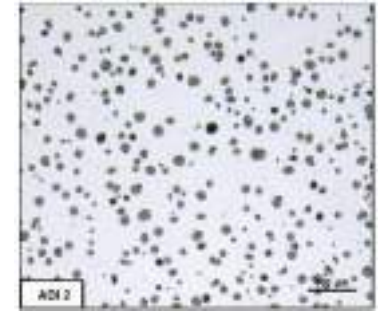
- Damage Rate = $\frac{\% \text{ pitting area}}{\text{number of load cycle}}$



- Temperatura de austêmpera
- Tamanho de nódulos
- Distribuição de nódulos
- Propriedades da matriz



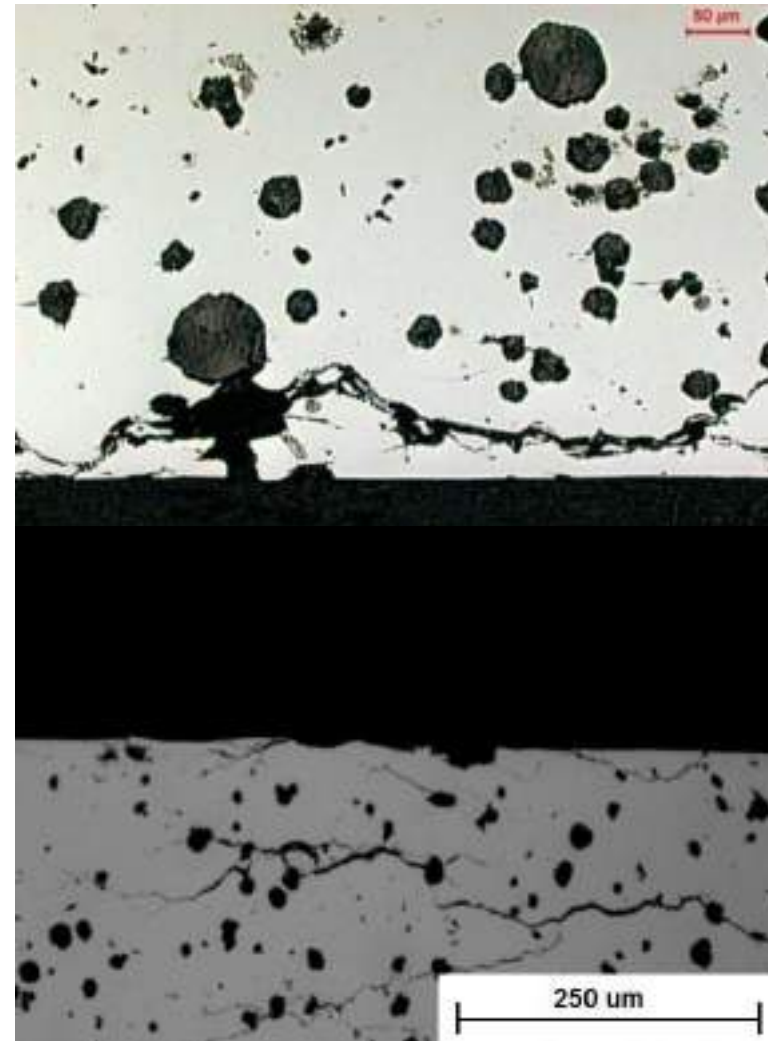
ADI 1



ADI 2

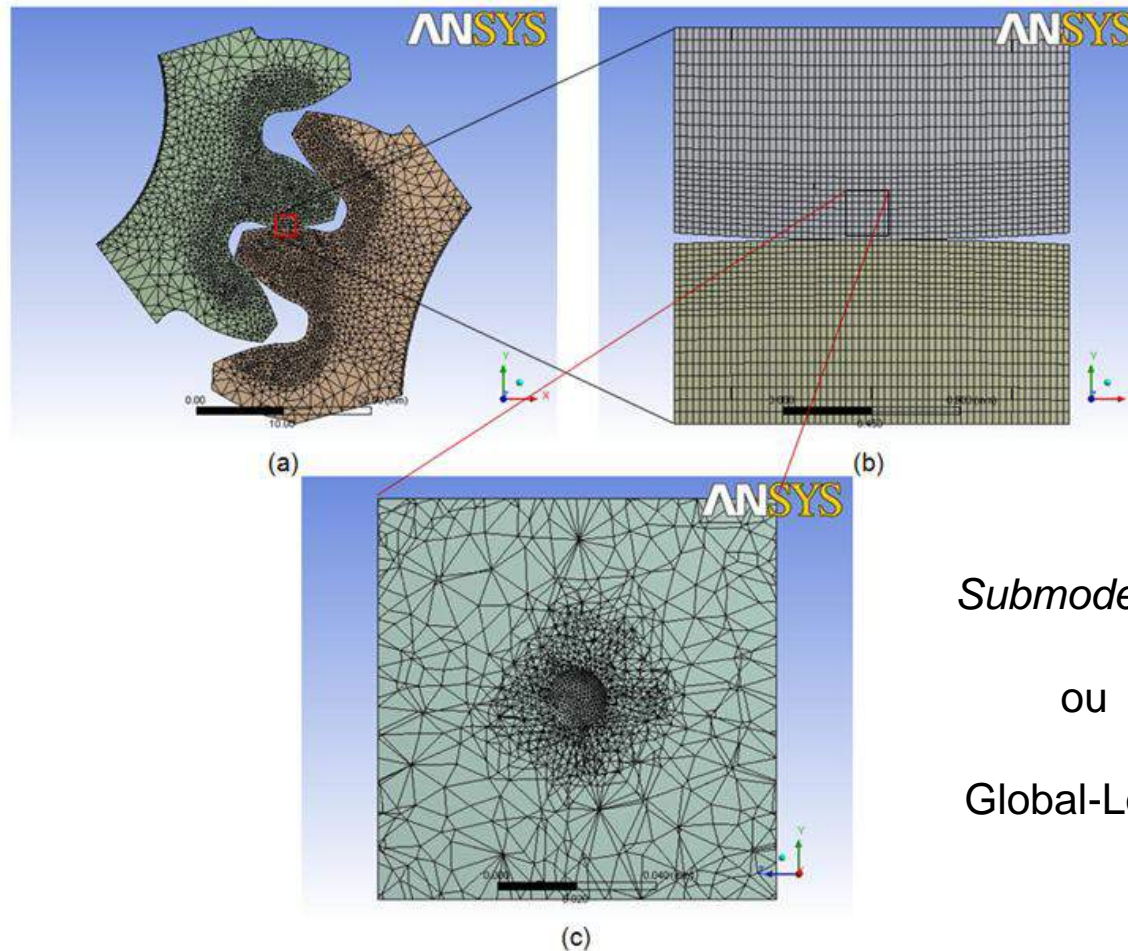
- ADI 1 versus ADI2

- ❑ Size of graphite nodules
- ❑ Stress Concentration
(**nucleation** of cracks)
- ❑ Crack branching mechanism
(**propagation** of cracks)
Greno et al., 1999
- ❑ The state of stress in contacts with smaller nodules is less severe
(**propagation** of cracks)
Dommarco et al., 2006



Numerical Analysis of the Influence of Graphite Nodule Size on the Pitting Resistance of Austempered Ductile Iron Gears

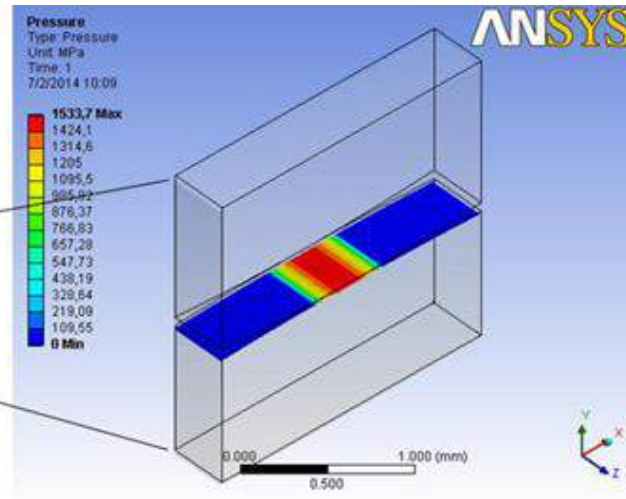
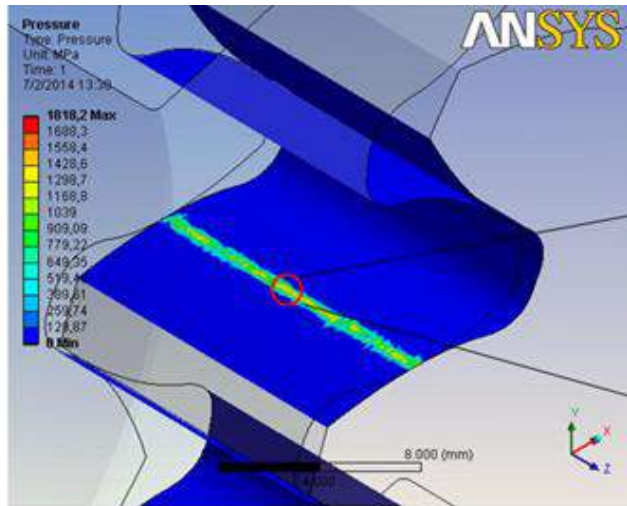
LUIZ Henrique Accorsi Gans^{1,a}, WILSON Luiz Guesser^{2,b},
MARCO Antonio Luersen^{1,c} and CARLOS Henrique da Silva^{1,d}



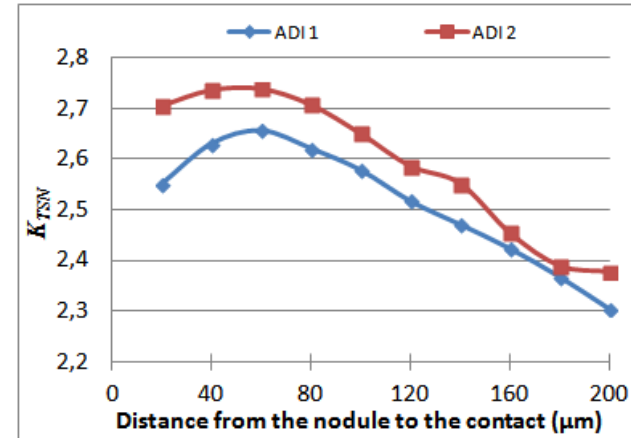
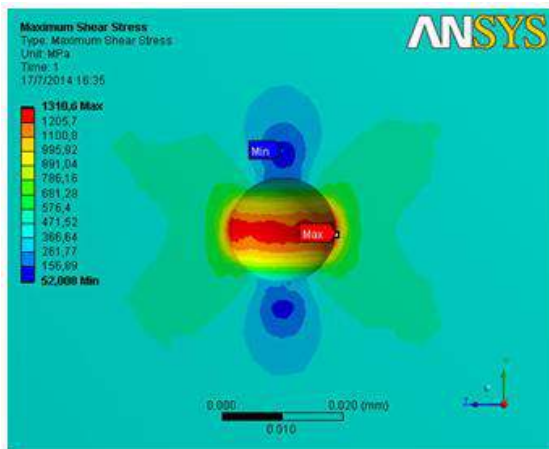
Submodelling

ou

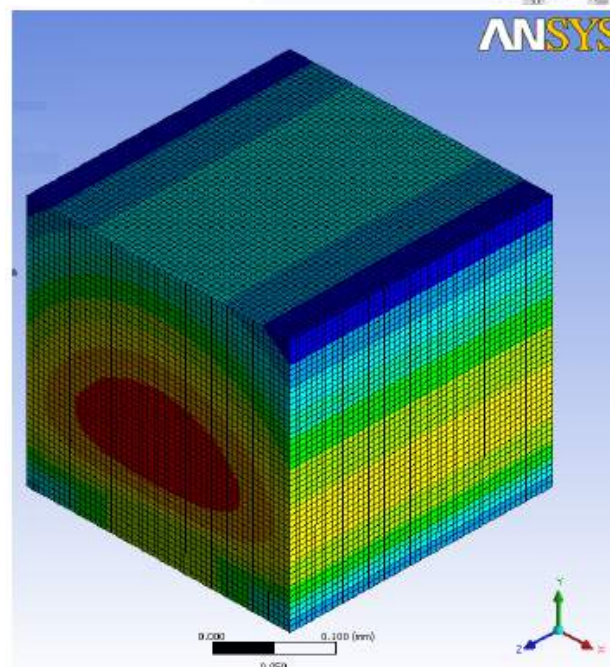
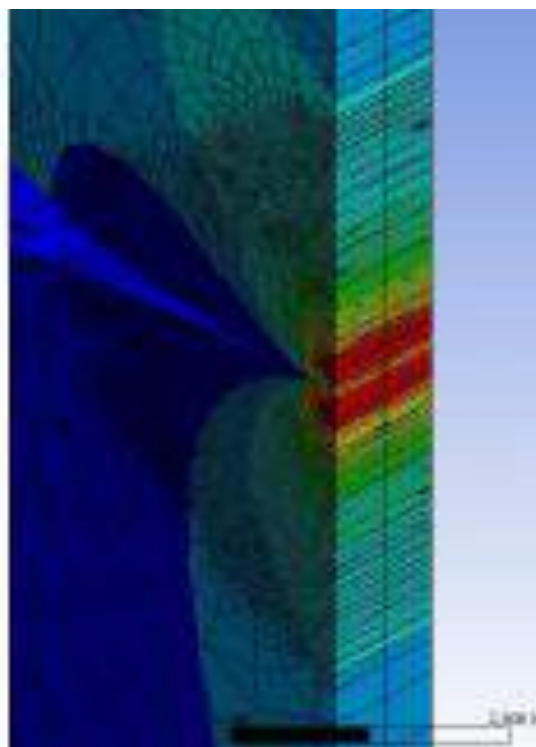
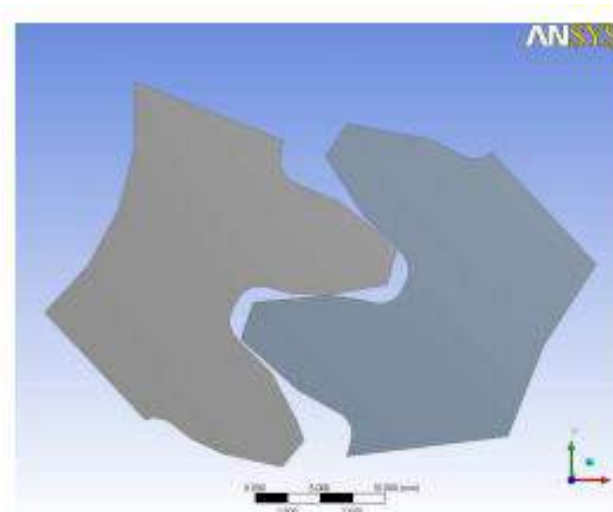
Global-Local

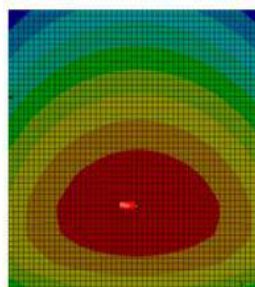


$$K_{TSN} = \frac{\tau_{\text{maximum shear stress with nodules}}}{\tau_{\text{maximum shear stress without nodules}}}$$

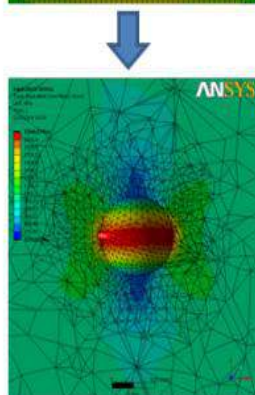


JAQUELINE LAZZARON
(BOLSISTA PIBIC – CNPq)

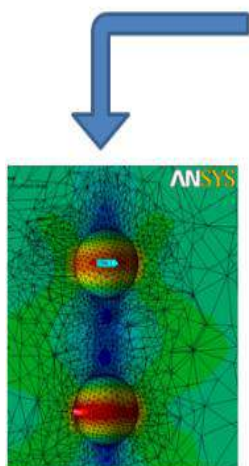




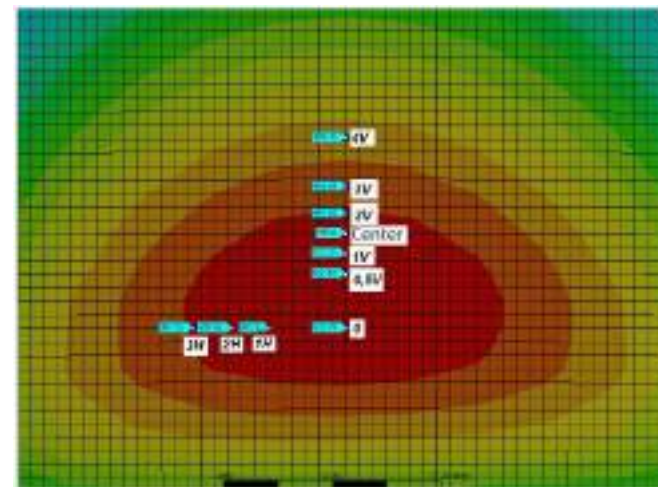
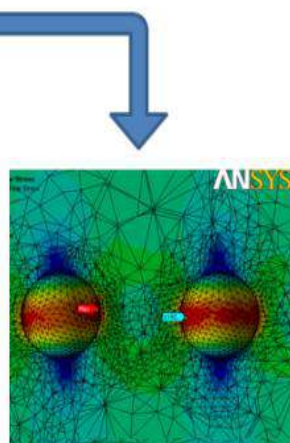
1ª análise
(sem nódulos)



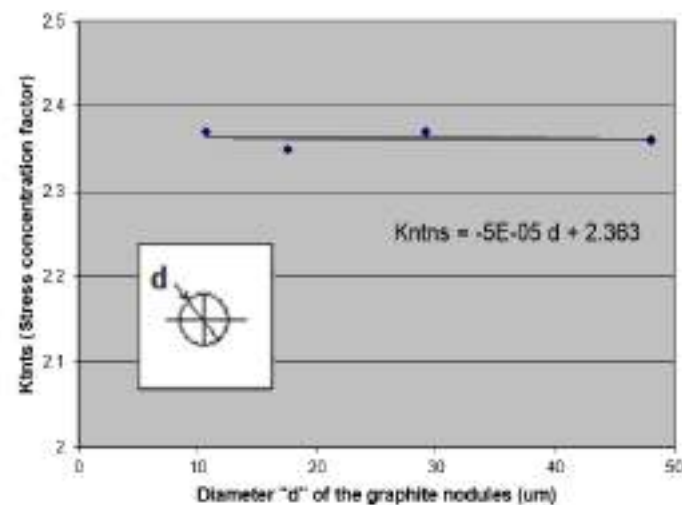
2ª análise
(1 nódulo sozinho)



3ª análise
2 nódulos posicionados na
vertical e na horizontal

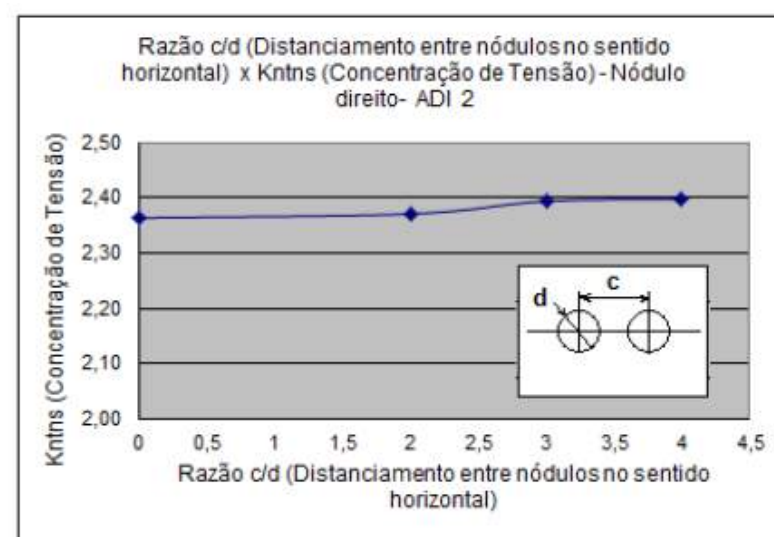
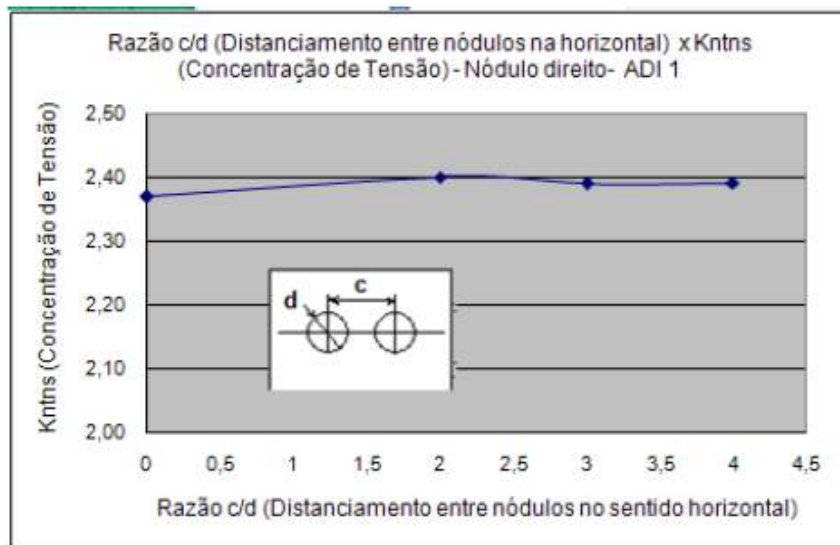
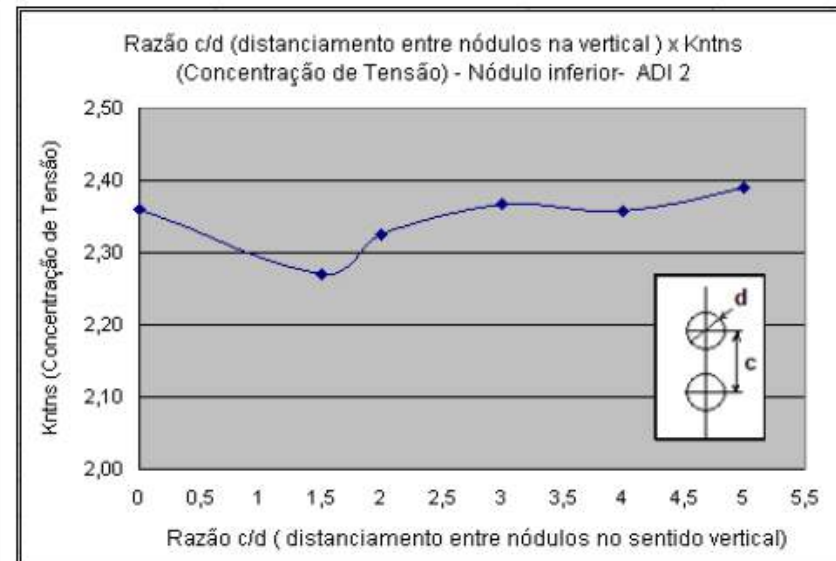
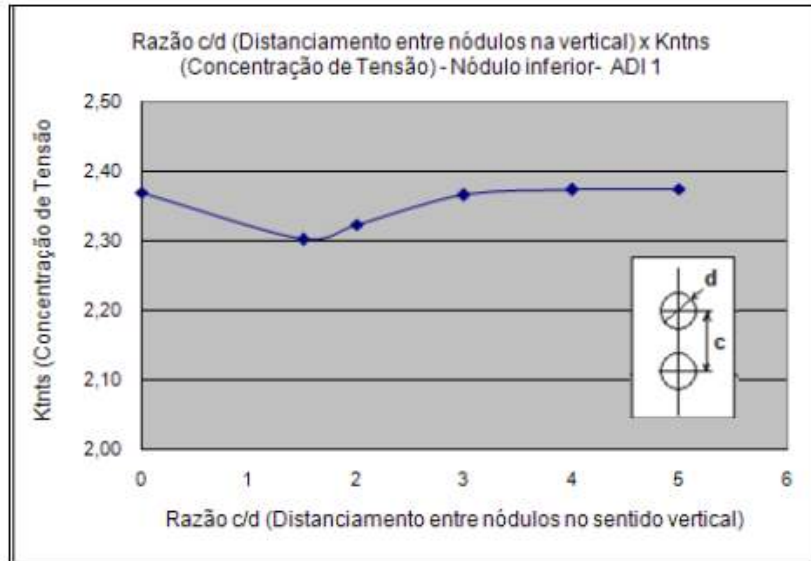


$$K_{ntns} = \frac{\tau_{with\ nodules}}{\tau_{without\ nodules}}$$



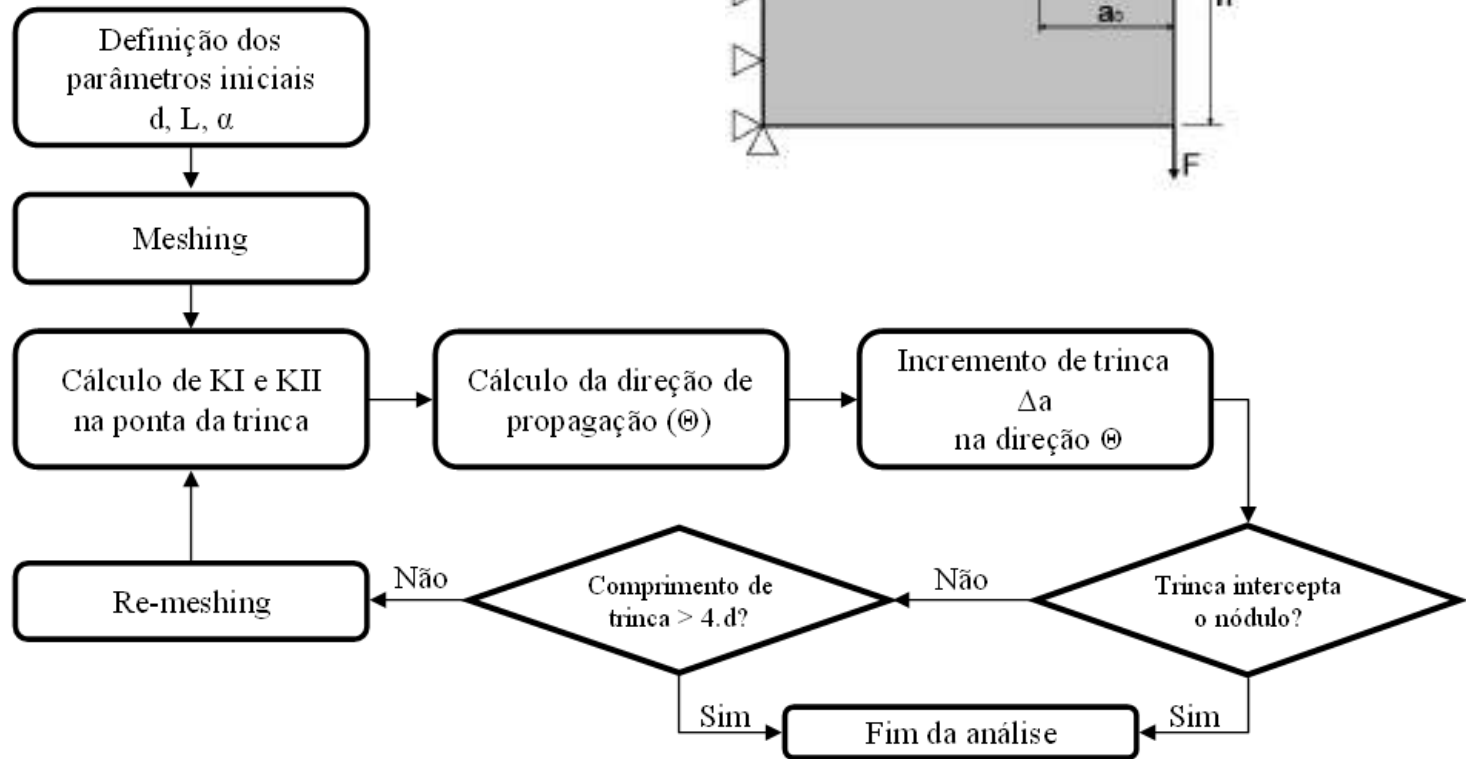
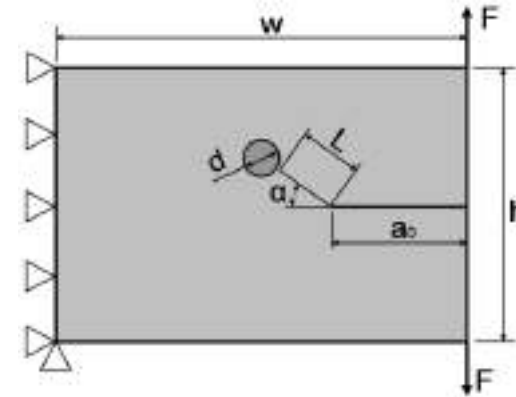
Efeito da presença de nódulos vizinhos

VERTICAL



HORIZONTAL

ESTUDO DE PROPAGAÇÃO DE TRINCAS

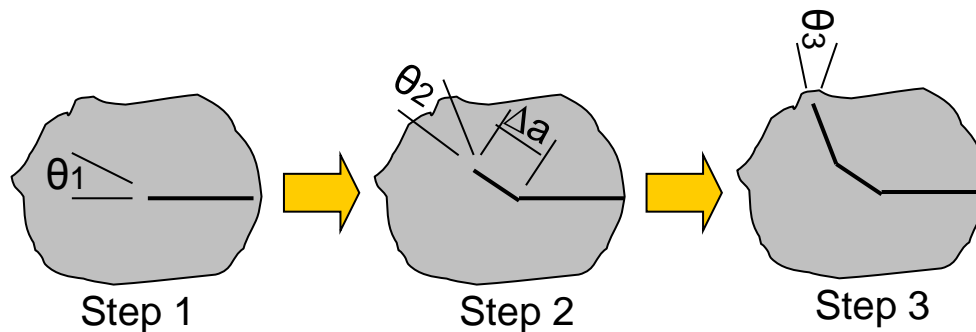
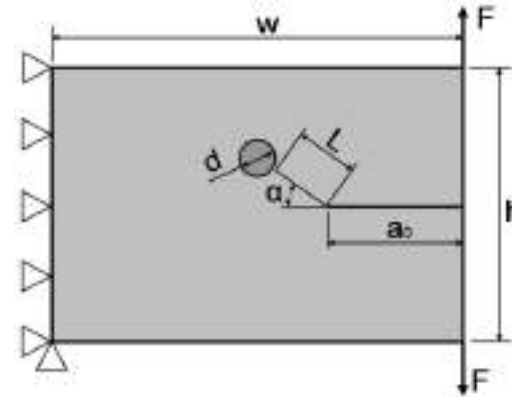


✓ *Re-meshing* – incrementos de comprimento de trinca e atualização da malha

ESTUDO DE PROPAGAÇÃO DE TRINCAS

$$\theta = \cos^{-1} \left(\frac{3K_{II}^2 + \sqrt{K_I^2 + 8K_I^2 K_{II}^2}}{K_I^2 + 9K_{II}^2} \right)$$

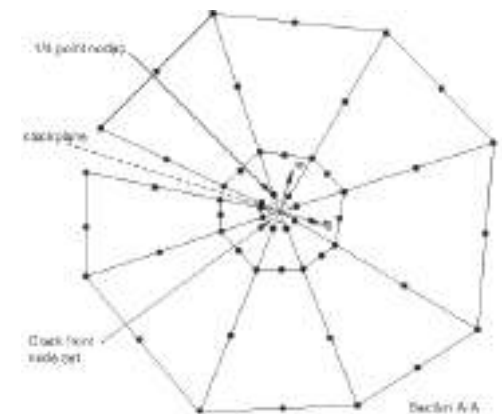
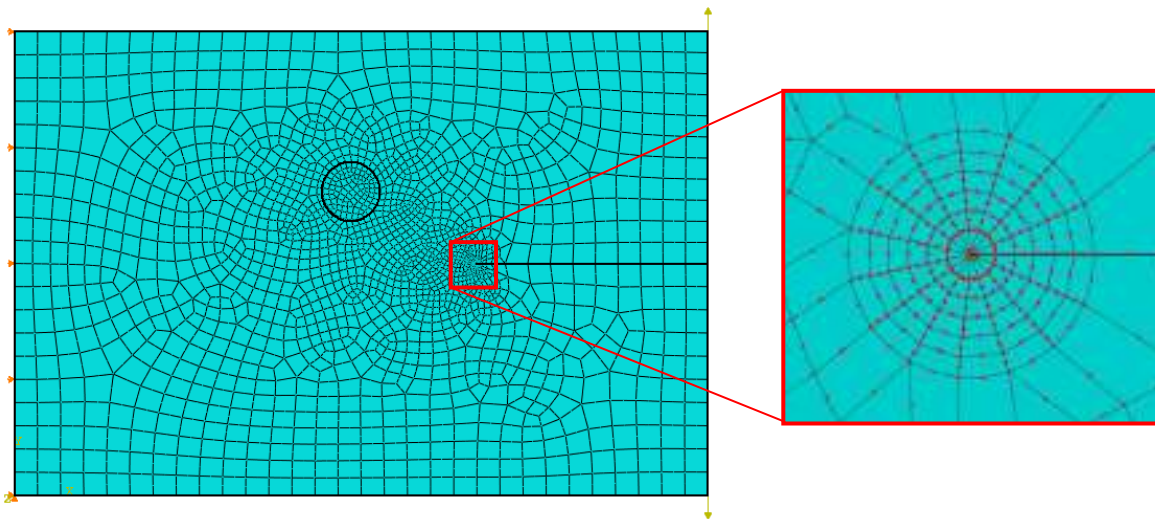
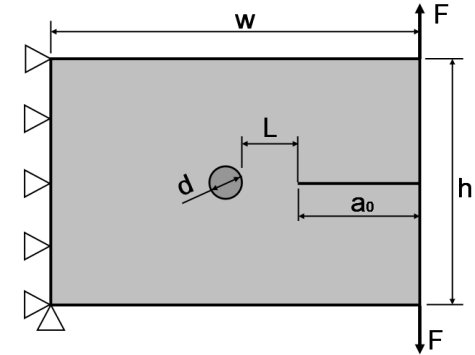
(ERDOGAN & SIH, 1963)



$$\frac{da}{dN} = C (\Delta K)^m$$

CONSIDERAÇÕES DO MODELO

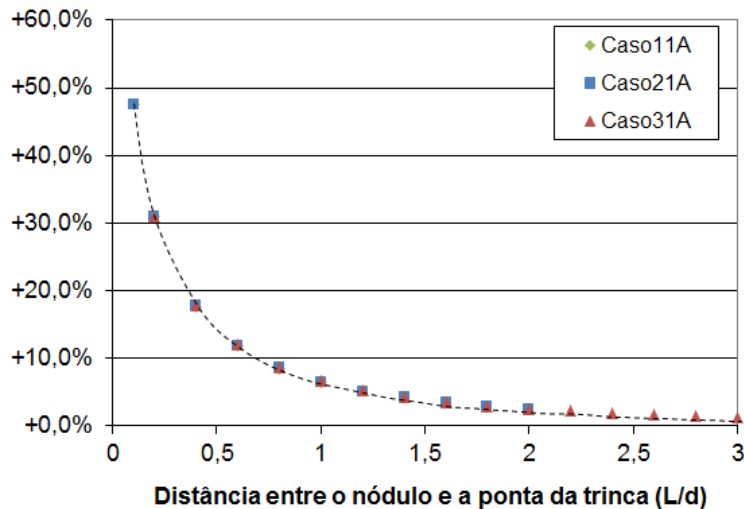
- ✓ Bidimensional;
- ✓ Estado plano de deformações (EPD);
- ✓ Incrementos de comprimento de trinca constantes (Δa);
- ✓ Elementos quadriláteros de segunda ordem;
- ✓ Ponta de trinca
 - ❑ Elementos triangulares singulares tipo *quarter-points* (singularidade $1/r^{0,5}$ em tensão).



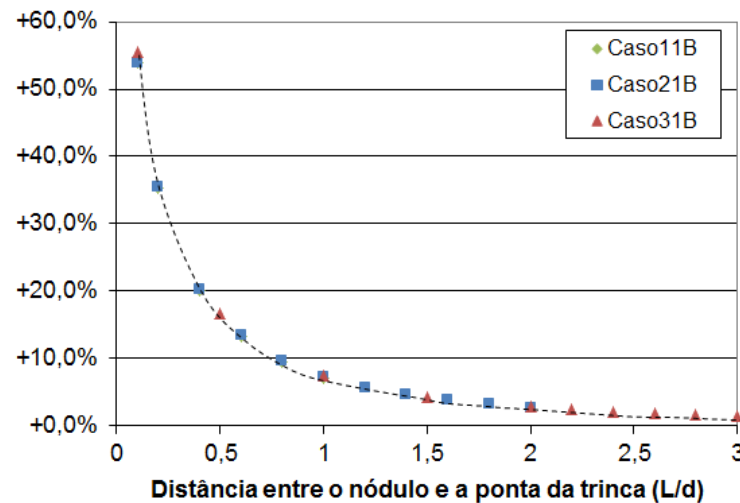
$\alpha = 0^\circ$

AUMENTO PERCENTUAL DE K_I EM RELAÇÃO À AUSÊNCIA DE NÓDULO

Nódulo menor (A)



Nódulo maior (B)



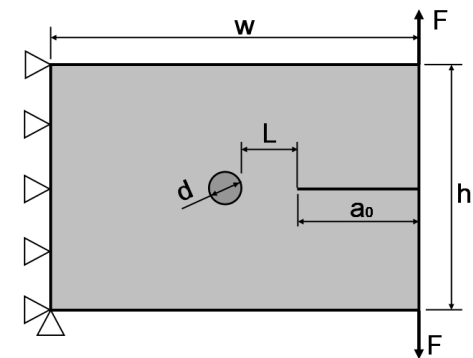
✓ Valores de K_{II} nulos ou desprezíveis (inferiores a 0,05% de K_I).

✓ Direção de propagação nulos ou desprezíveis
(na ordem de 0,001 grau).

✓ Observa-se um aumento de K_I com a presença do nódulo.

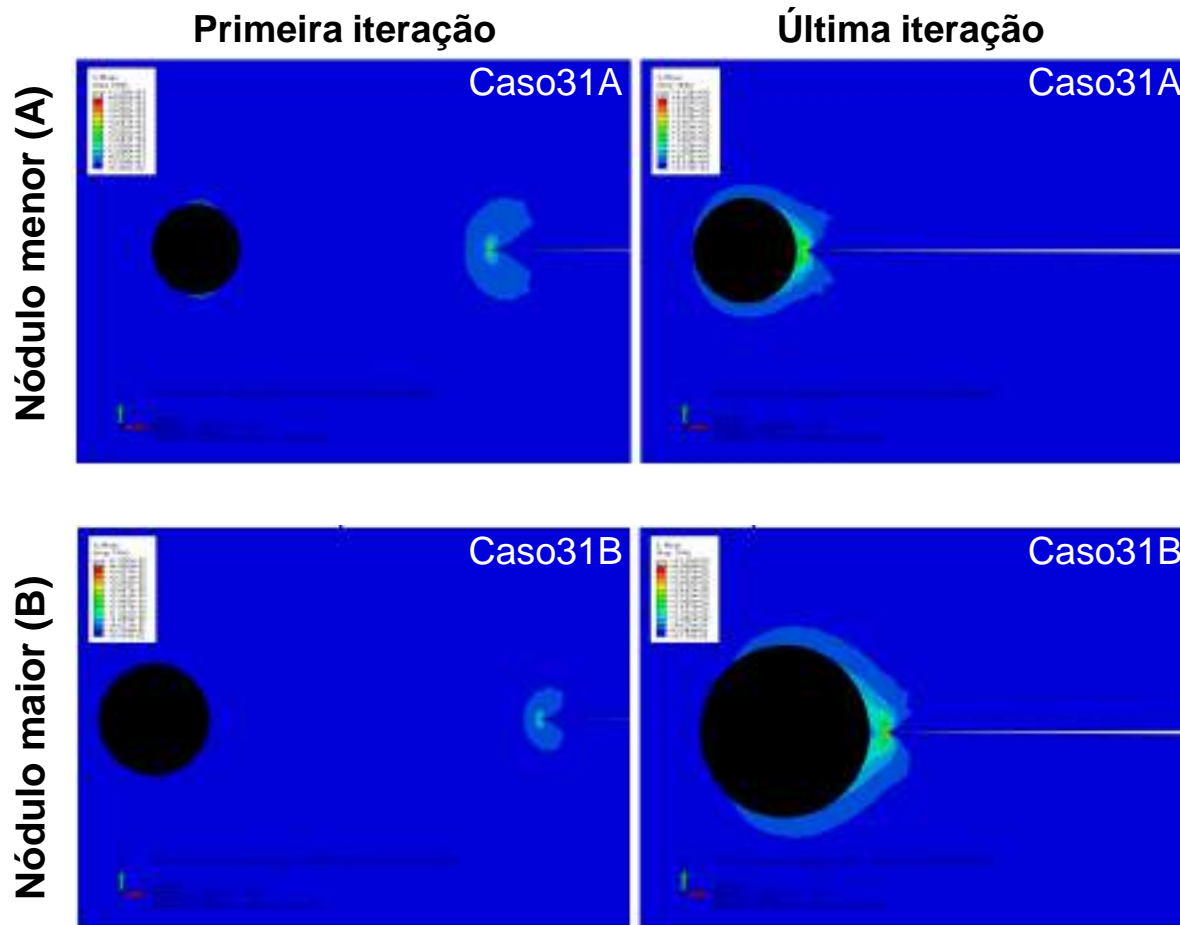
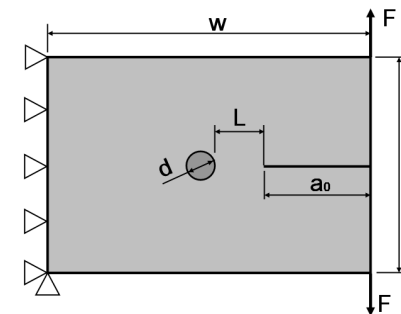
✓ K_I aumenta progressivamente conforme a trinca se aproxima do nódulo.

✓ Casos com maior diâmetro de nódulo (B) apresentam maiores valores de K_I



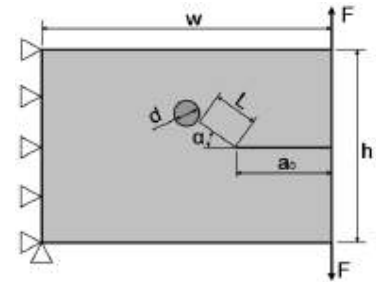
$\alpha = 0^\circ$

CAMPO DE TENSOES (VON-MISES)



$\alpha = 30^\circ$

CAMPO DE TENSOES (VON-MISES)

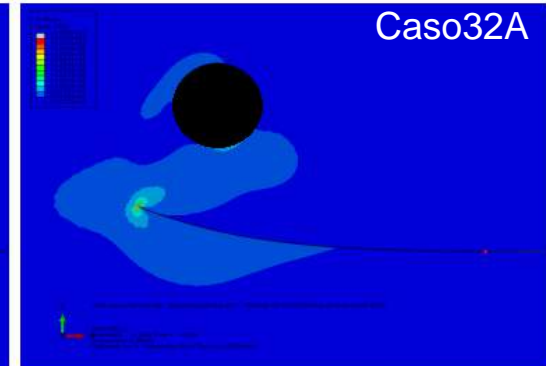
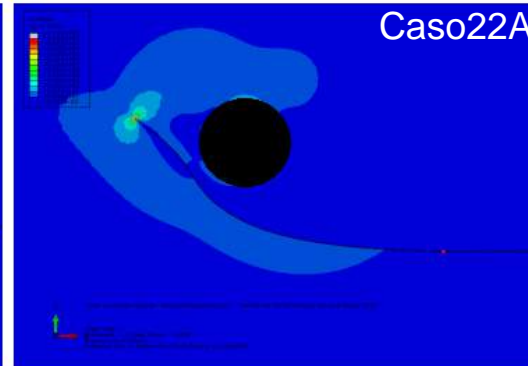
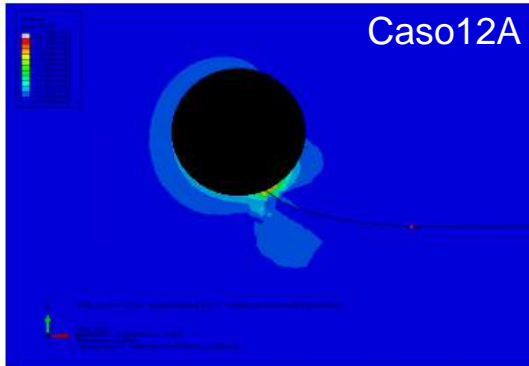


L = 1d

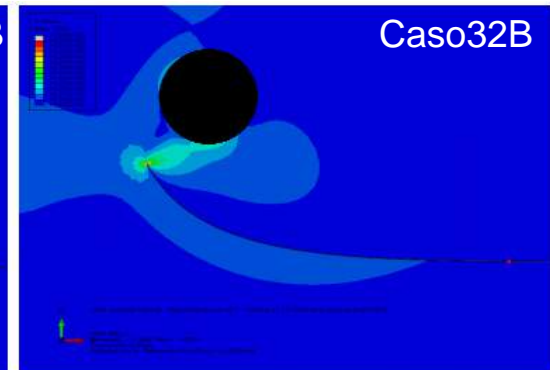
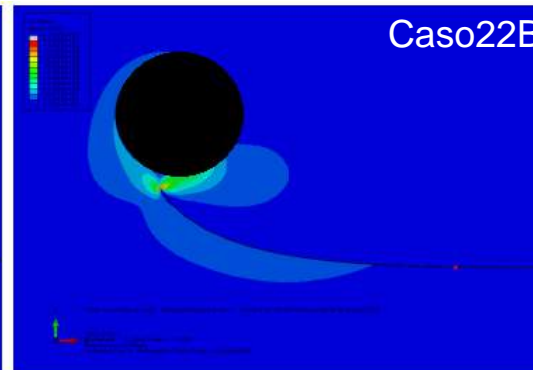
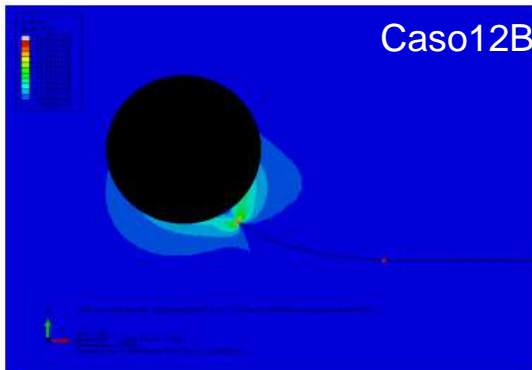
L = 2d

L = 3d

Nódulo menor (A)

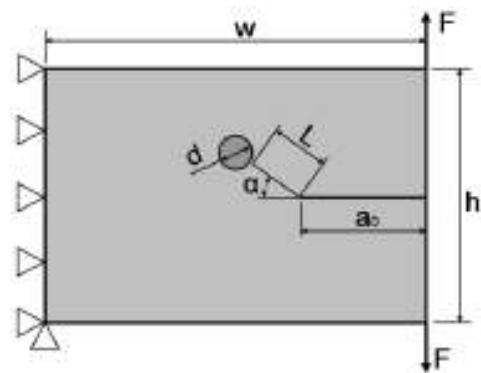
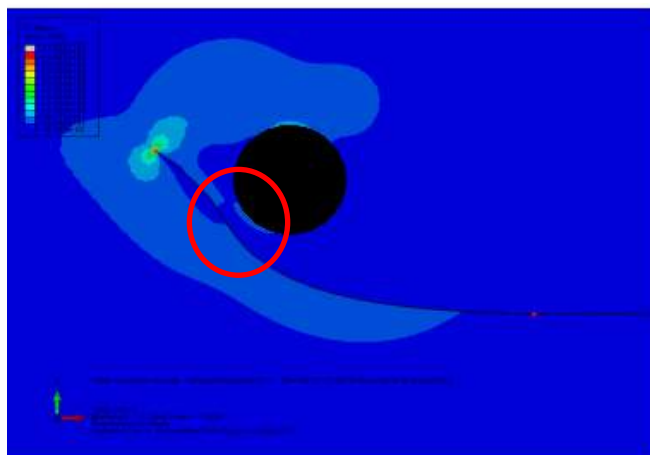


Nódulo maior (B)

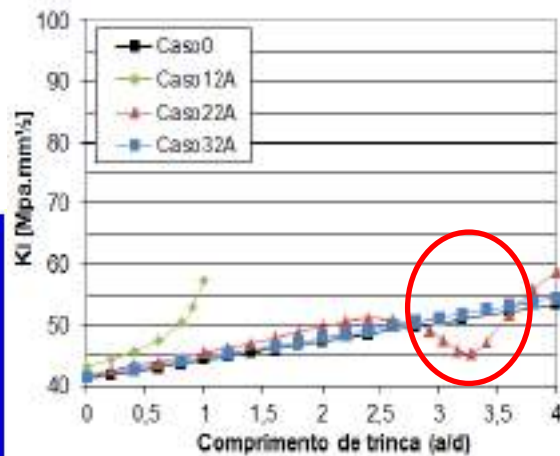


✓ Caso 22A

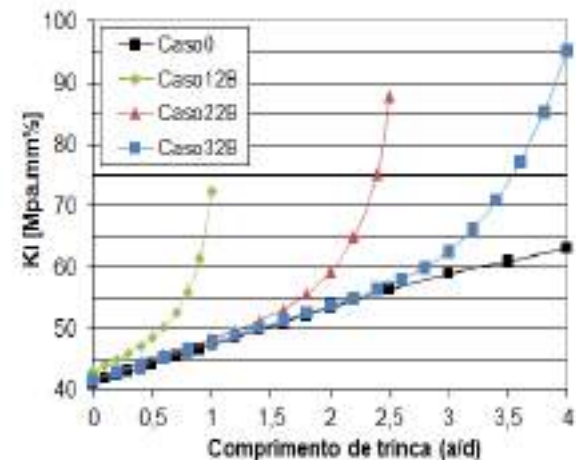
- K_I e K_{II} não são estritamente crescentes durante a propagação da trinca



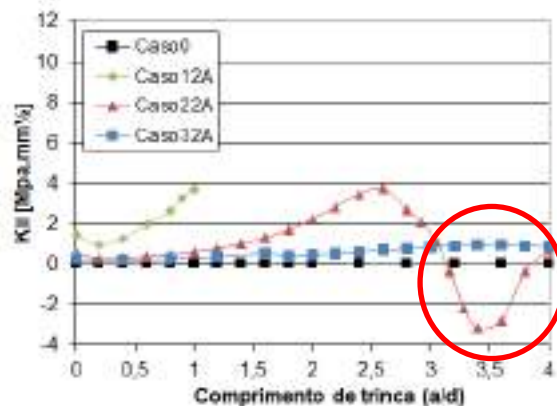
Nódulo menor (A)



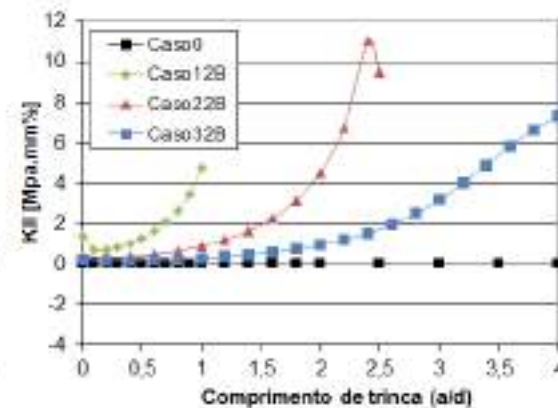
Nódulo maior (B)

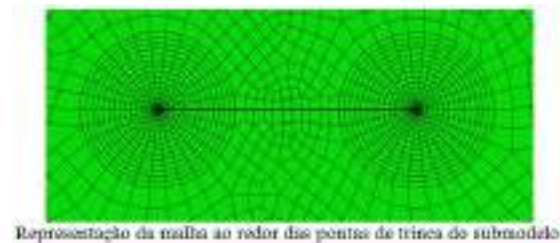
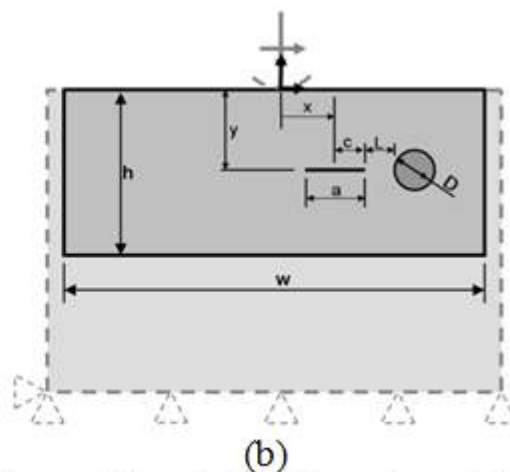
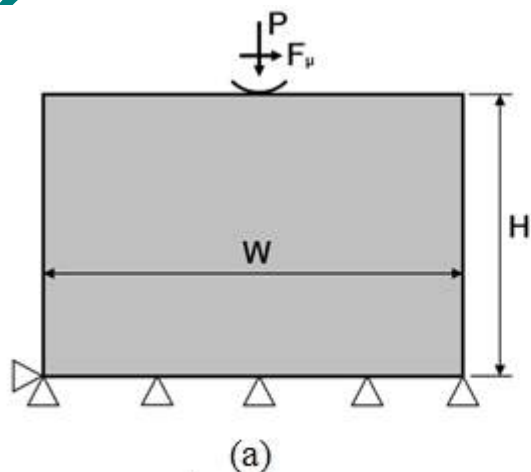


Nódulo menor (A)



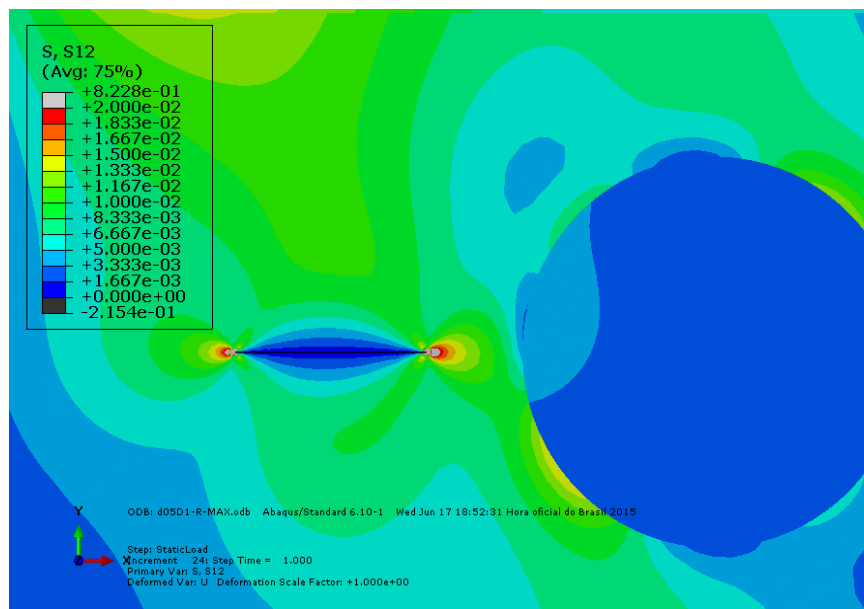
Nódulo maior (B)



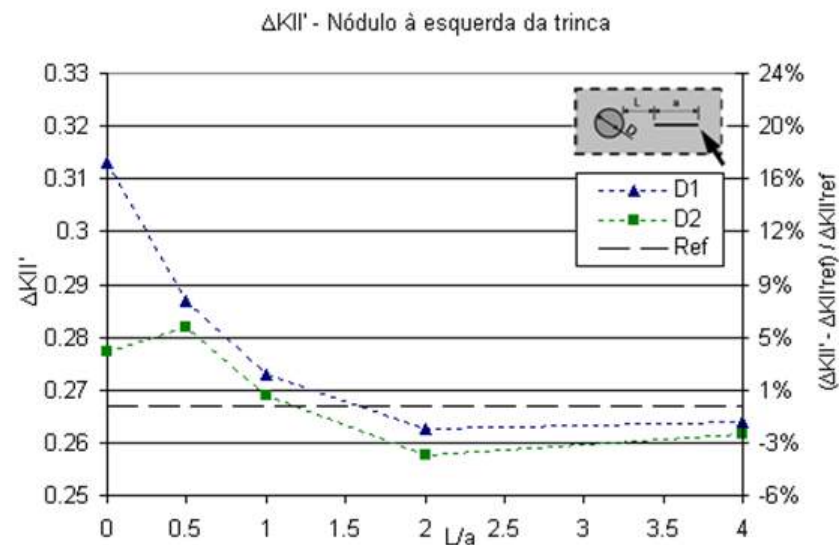
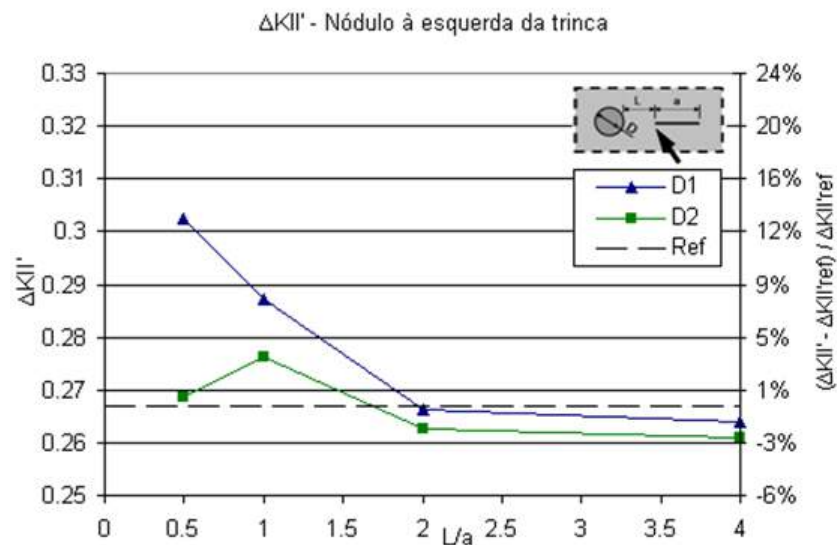
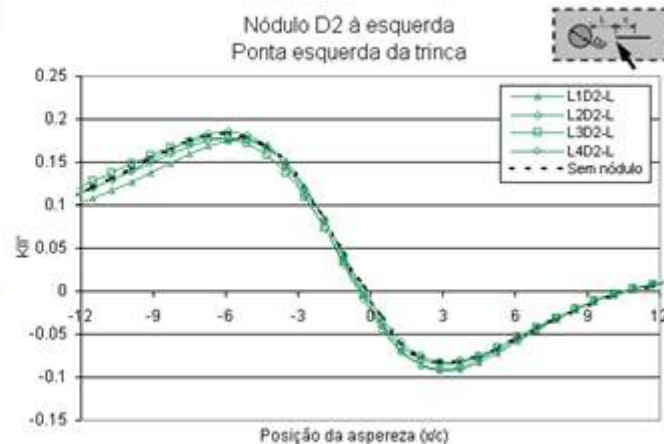
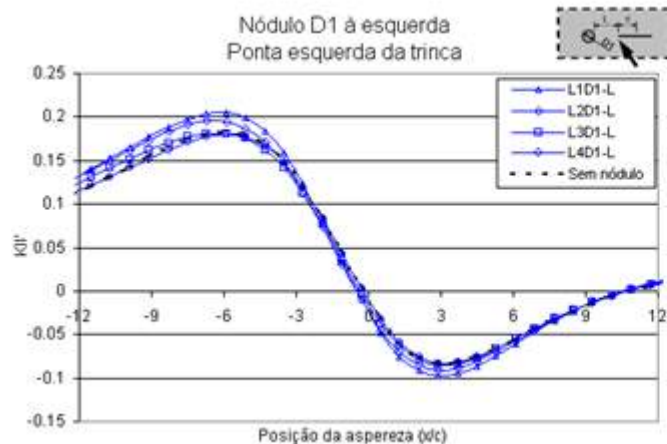


Representação das dimensões e carregamento do modelo global (a) e submodelo (b)

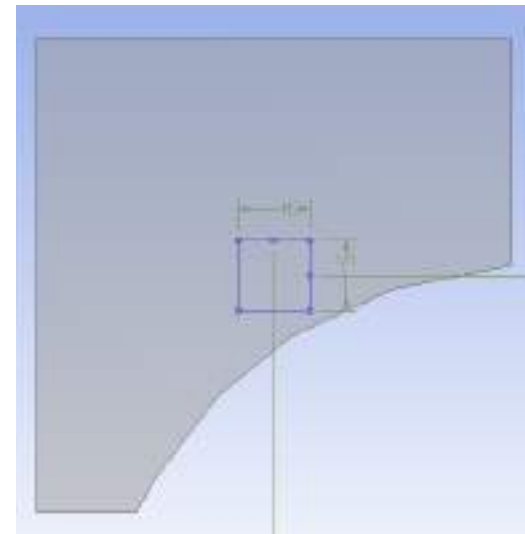
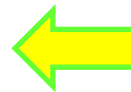
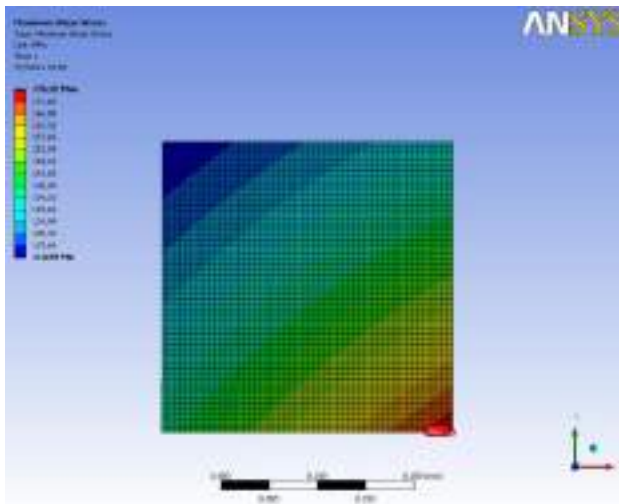
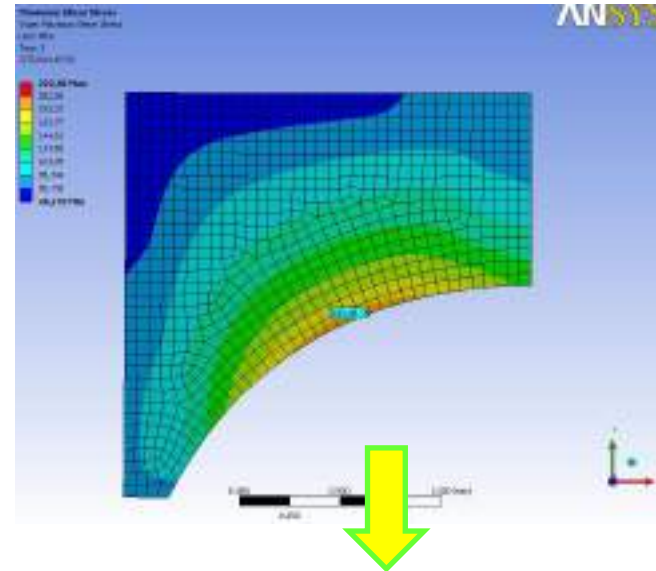
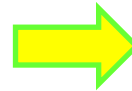
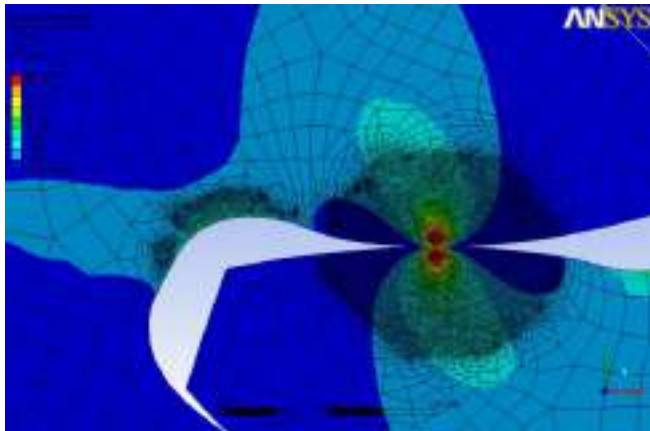
Acompanhamento do campo de tensões e dos fatores K_I e K_{II}



Distância = 0,5a



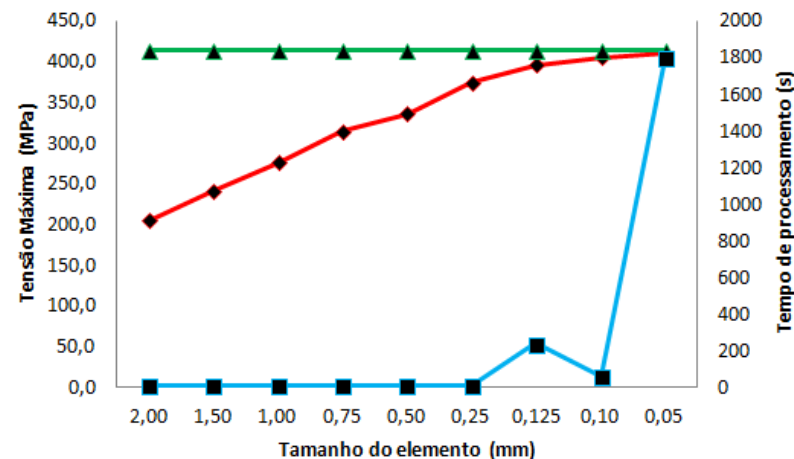
TCC – Victor Betim / Pedro Murilo - 2015
Profa Ana Paula Junqueira



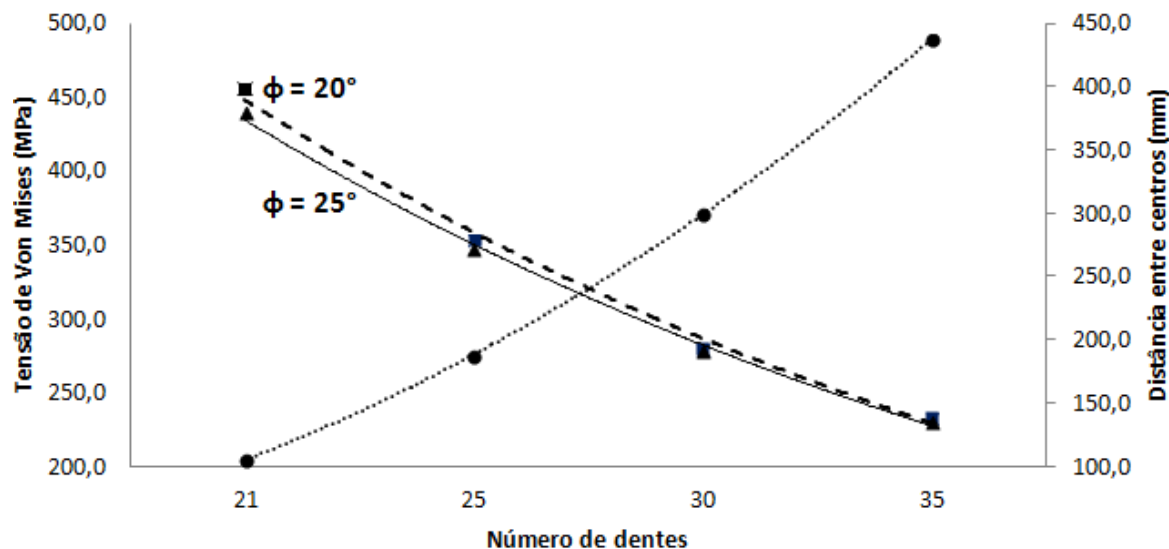
TCC – Victor Betim / Pedro Nunes - 2015
Prof^a Ana Paula Junqueira

- Geometria da Raiz
- Convergência
- Análises de parâmetros

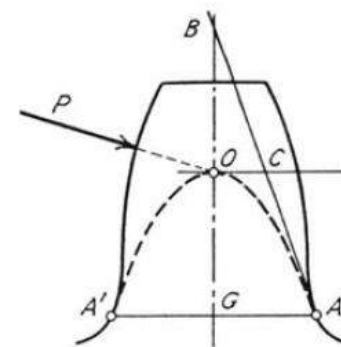
- Módulo
- Ângulo

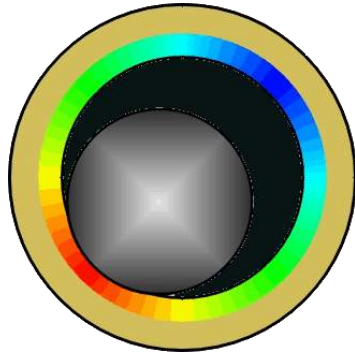


◆ Tensão Máxima ▲ Tensão Analítica (MPa) ■ Tempo de análise (s)

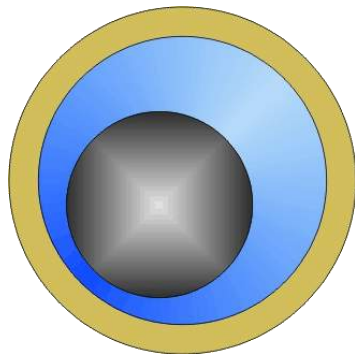


■ Tensão de Von Mises $\phi = 20^\circ$ ▲ Tensão de Von Mises $\phi = 25^\circ$ ● Distância entre centros

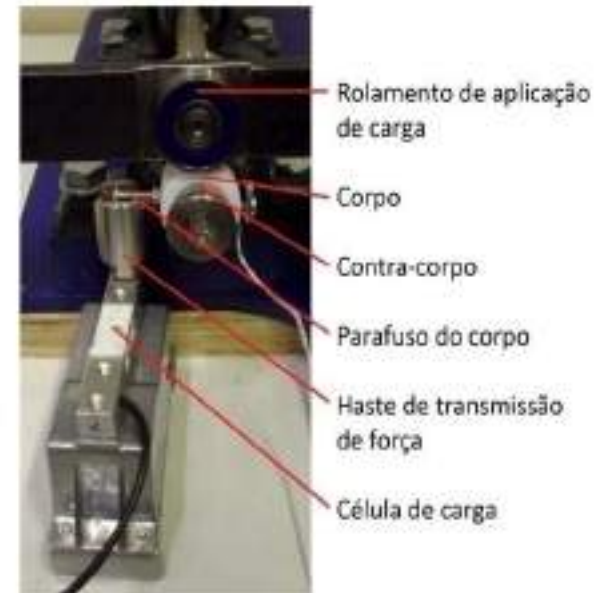
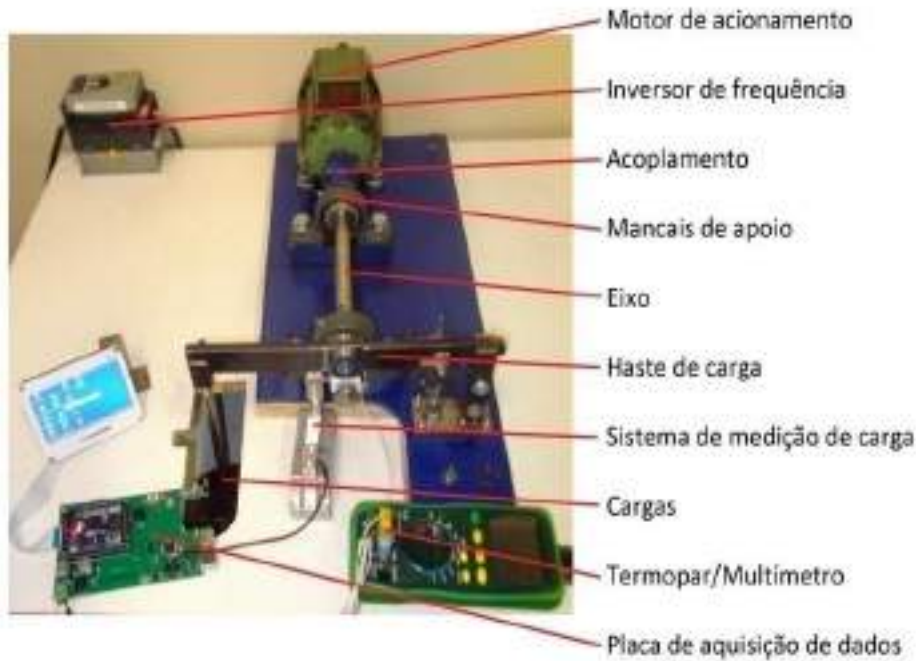




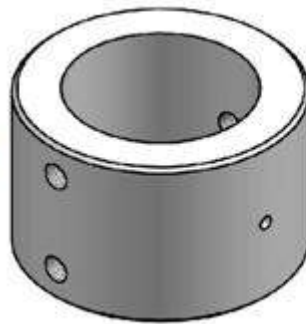
FILME DE ÓLEO COM DILUIÇÃO



MANCAL POLIMÉRICO (autolubrificante)



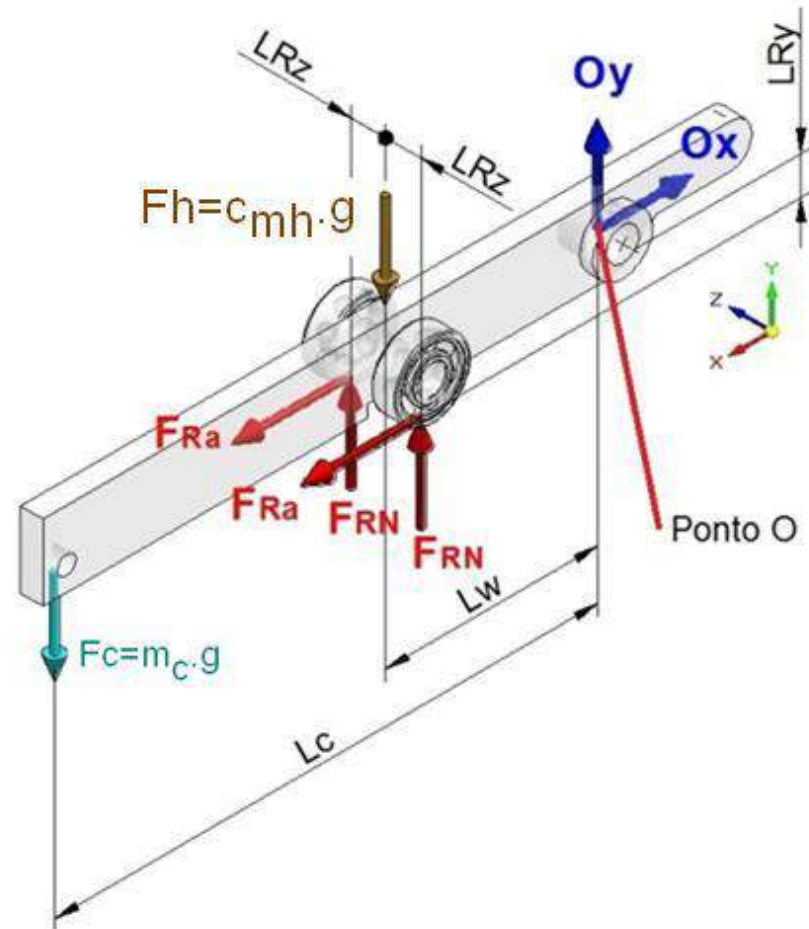
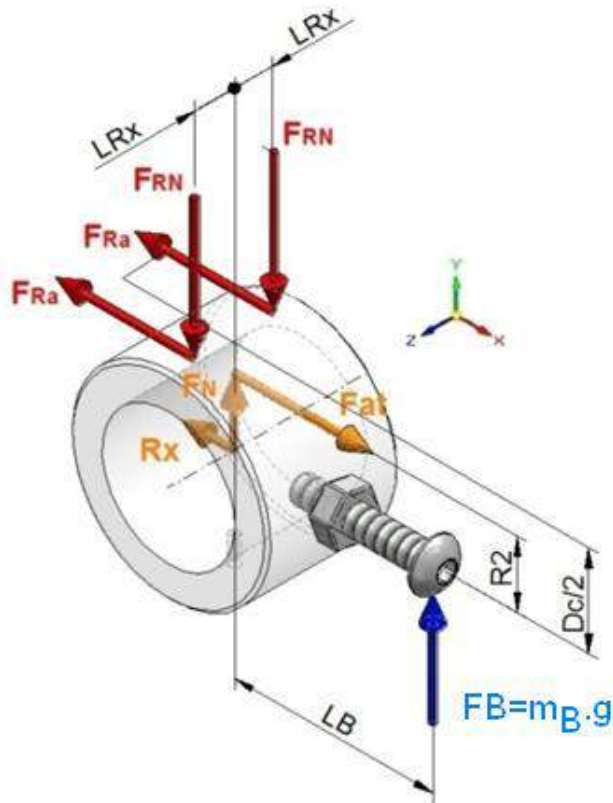
Corpo

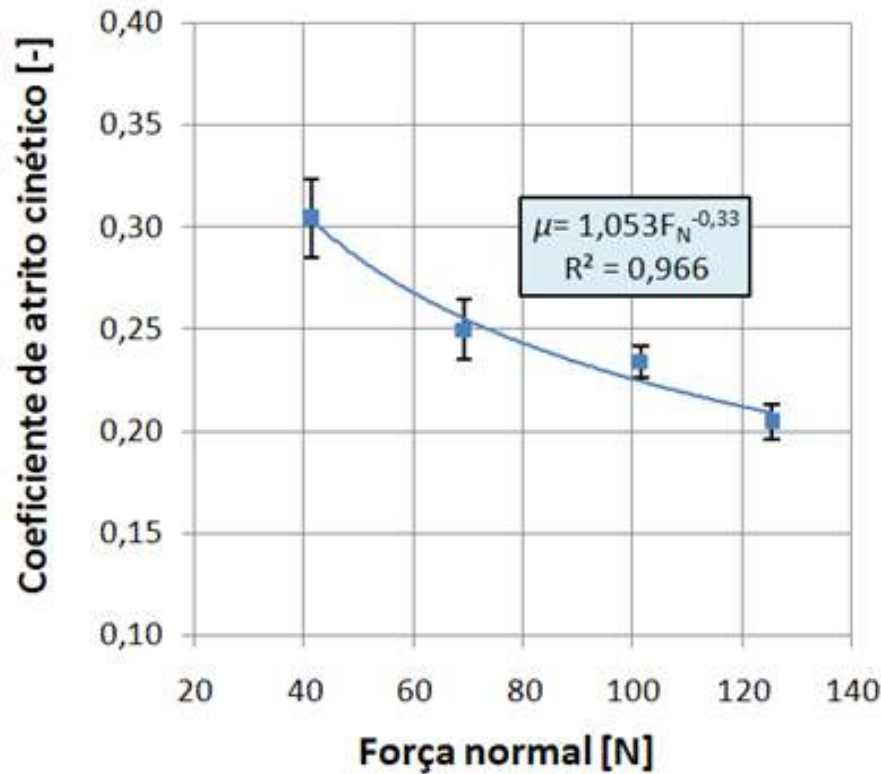


Contra-corpo



$$\mu = f(m_B, m_c) = \frac{\frac{1}{R_2} (L_B m_B)}{\frac{L_c}{L_w} m_c + c_{mh} - m_B}$$





- ◆ Excelente aproximação com o modelo de atrito de Archard (1957)

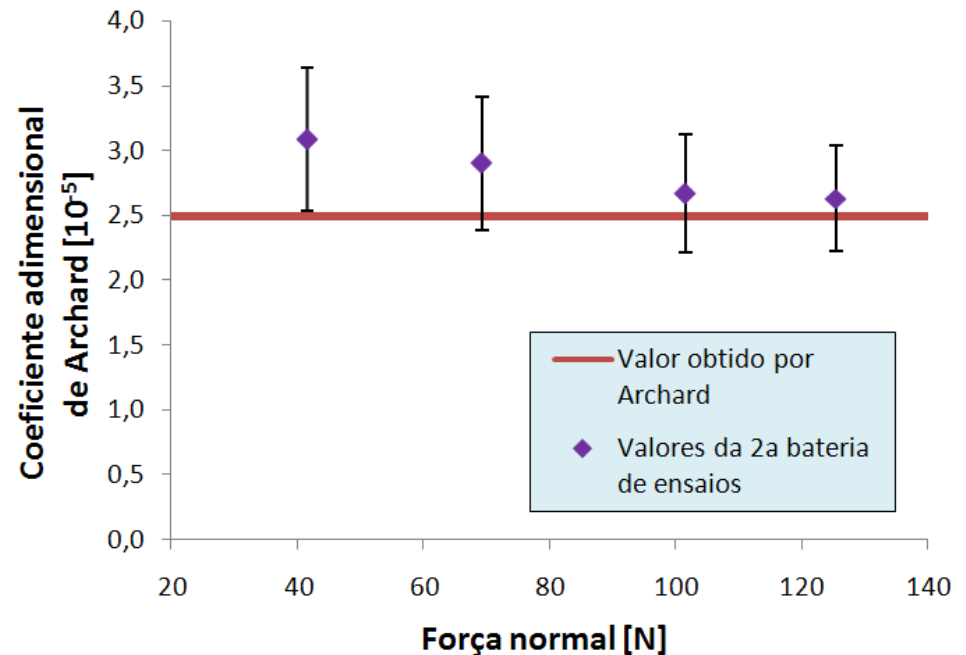
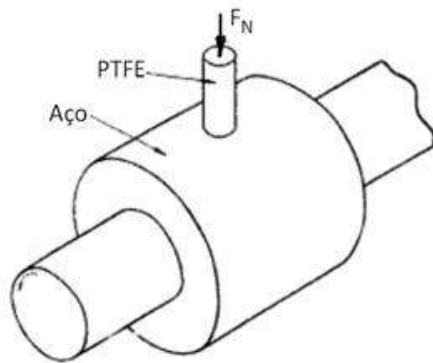
Valores médios do coeficiente de atrito cinético, para os quatro níveis de força normal, considerando somente os últimos 20 minutos de ensaio.

Nível 01	Nível 02	Nível 03	Nível 04
0,304 ± 0,020	0,250 ± 0,015	0,235 ± 0,008	0,204 ± 0,008

$$Q = K \frac{F_N}{H}$$

Q : Taxa de volume desgastado por distância de deslizamento [m^3/m];
 K : Coeficiente de desgaste adimensional [-];
 F_N : Carregamento normal [N];
 H : Dureza da superfície mais mole [Pa].

- Segundo Archard e Hirst (1956):
 - Cada material tem um coeficiente adimensional de desgaste (PTFE: $2,5 \cdot 10^{-5}$);



- Aproximação satisfatória com o modelo;
- Mesmo com ensaios diferentes;

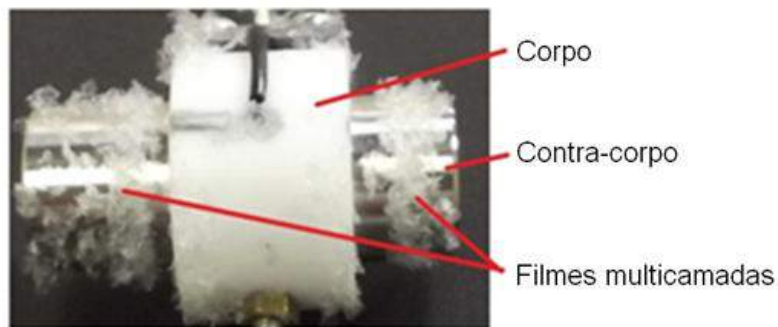


Figura 8. Fotografia de um par tribológico, após o ensaio de desgaste, com a condição típica de vários filmes multicamadas expulsos do contato.

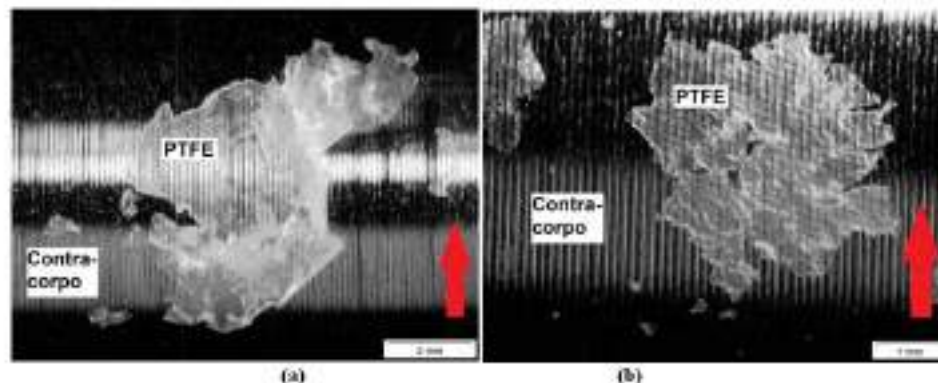


Figura 9. Imagens obtidas por estereoscopia mostrando contra-corpos após ensaio de desgaste (o sentido de deslizamento é indicado pela seta vermelha): (a) filme de PTFE aderido ao eixo de aço inoxidável, (b) detalhe de filme translúcido.

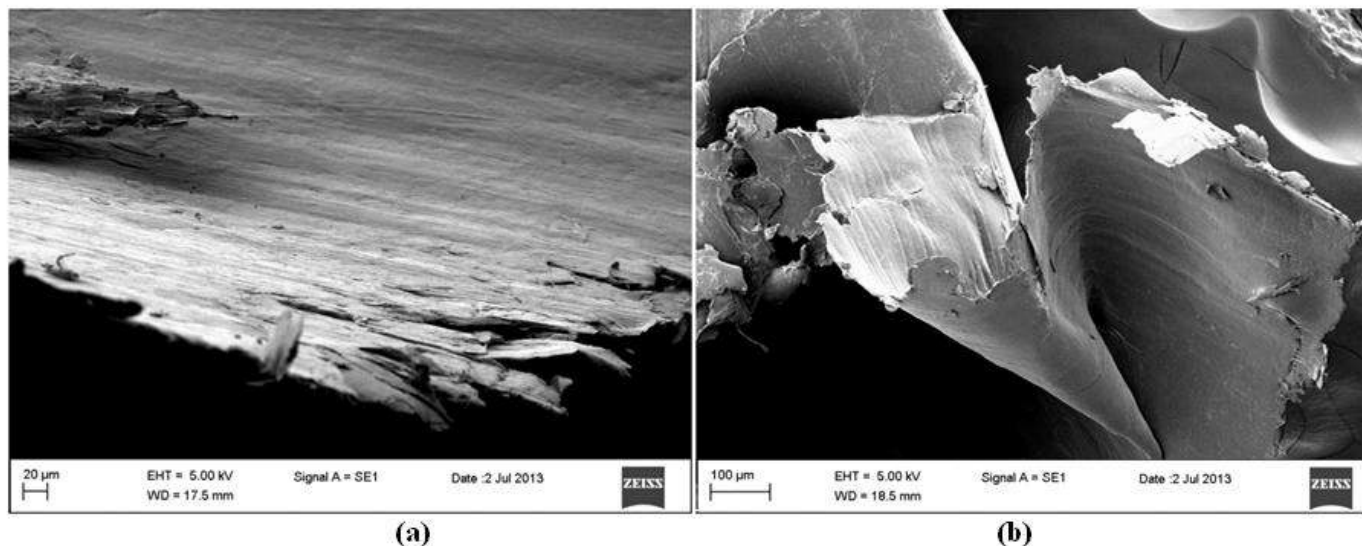


Figura 10. Imagens obtidas por MEV de filmes multicamadas: (a) detalhe das bordas do filme, (b) bordas deformadas mostrando as camadas.

Tabela 5. Resumo dos valores das DSCs para as amostras retiradas do corpo, antes e após ensaio de desgaste, e para os produtos do desgaste.

Amostra	Nível de força normal	Entalpia de fusão [J/g]	Temperatura de fusão [°C]	Grau de cristalinidade [%]
Condição original	Não ensaiado	32,8	330,8	39,9
Superfície desgastada	Condição 1	38,1	332,0	46,5
	Condição 2	35,8	330,4	43,7
	Condição 3	32,8	333,6	40,0
	Condição 4	35,6	330,6	43,5
	Média	35,6 ± 2,2	331,6 ± 1,5	43,4 ± 2,7
Produtos de desgaste	Condição 1	46,0	330,5	56,0
	Condição 2	47,1	331,1	57,4
	Condição 3	41,4	331,3	50,4
	Condição 4	46,3	336,4	56,5
	Média	45,2 ± 2,6	332,3 ± 2,7	55,1 ± 3,2

Estatisticamente iguais:

- Não houve degradação do material.

Aumento do grau de cristalinidade



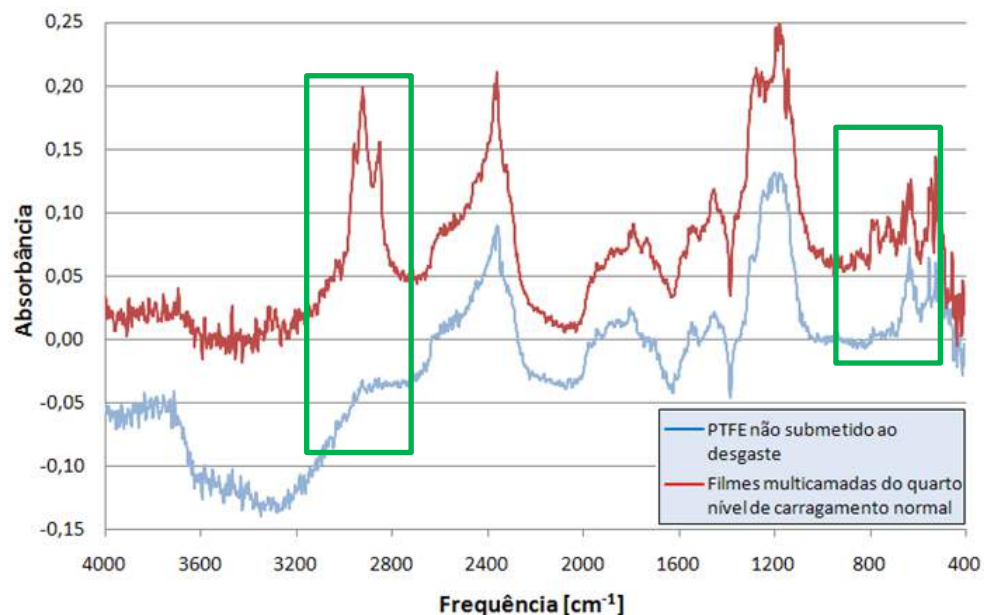
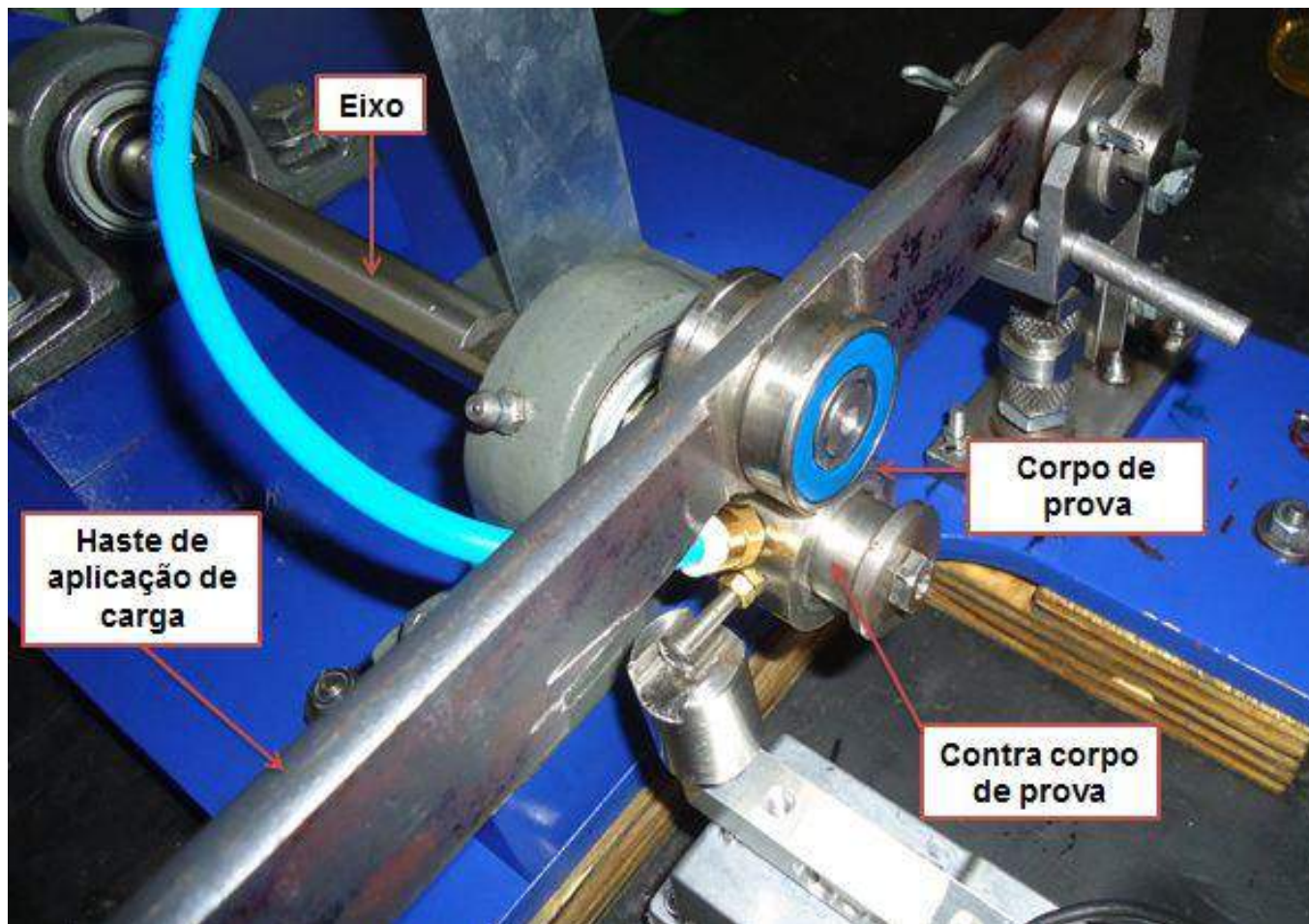
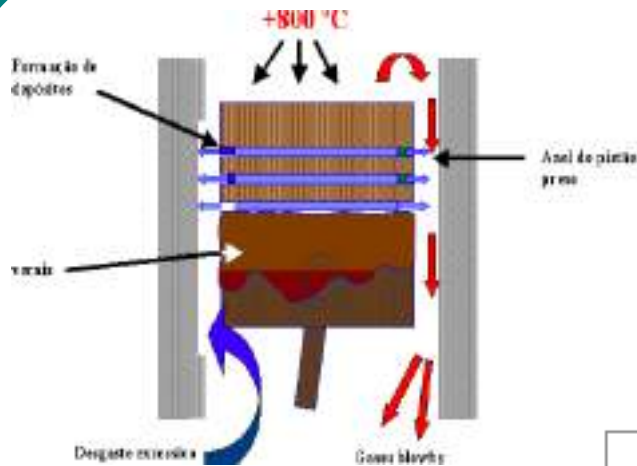


Figura 16. Espectros de FTIR para filmes multicamadas do quarto nível de carregamento normal e para PTFE não submetido ao ensaio de desgaste.

- Ocorrência de substituições:
 - de flúor por hidrogênio (H);
 - de flúor por hidroxilas (OH);
 - Possível formação de carbonila (C=O)
- Causa mais provável dessas alterações:
 - Presença de umidade e de oxigênio;
 - Elevação de temperatura;
 - Esforço mecânico envolvido durante o ensaio.





TCC: Eduardo Boasczyk, Leandro Taiatella e Thiago Martins

DILUIÇÃO POR GASOLINA

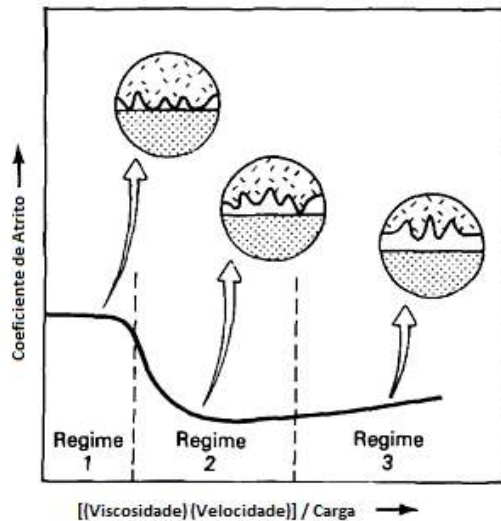
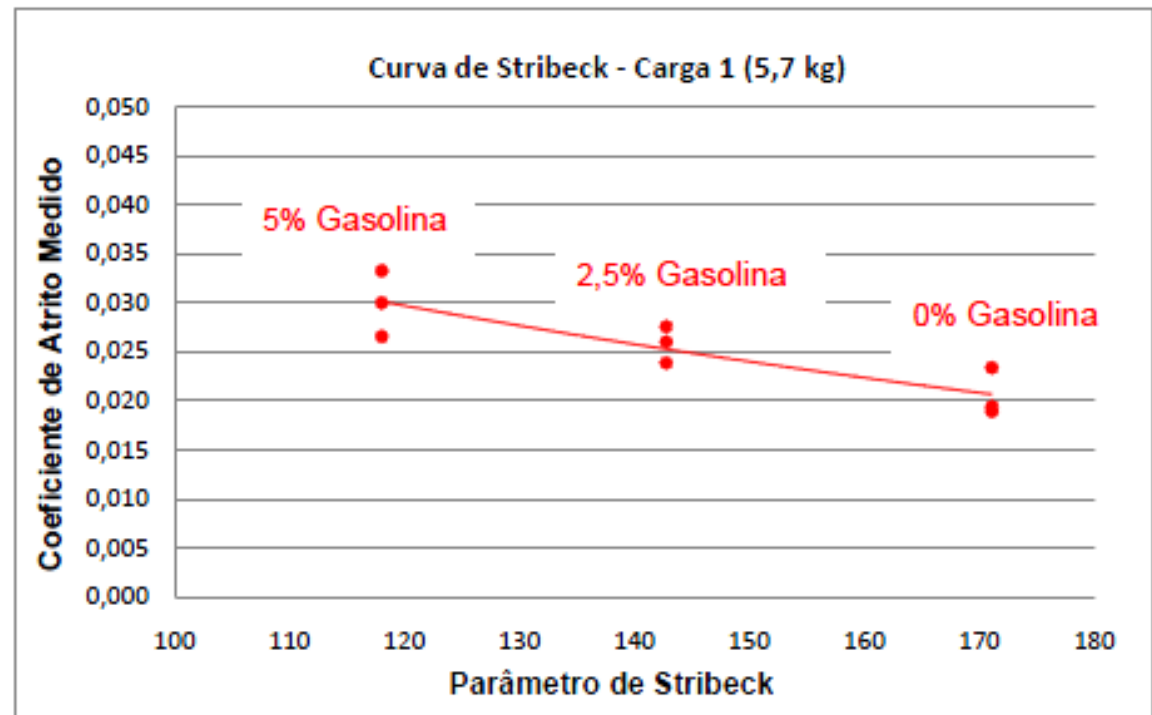


Diagrama de coeficiente de atrito X
 $(\text{Viscosidade}) \cdot (\text{Velocidade}) / \text{Carga}$

Fonte: ASM Handbook, 2006

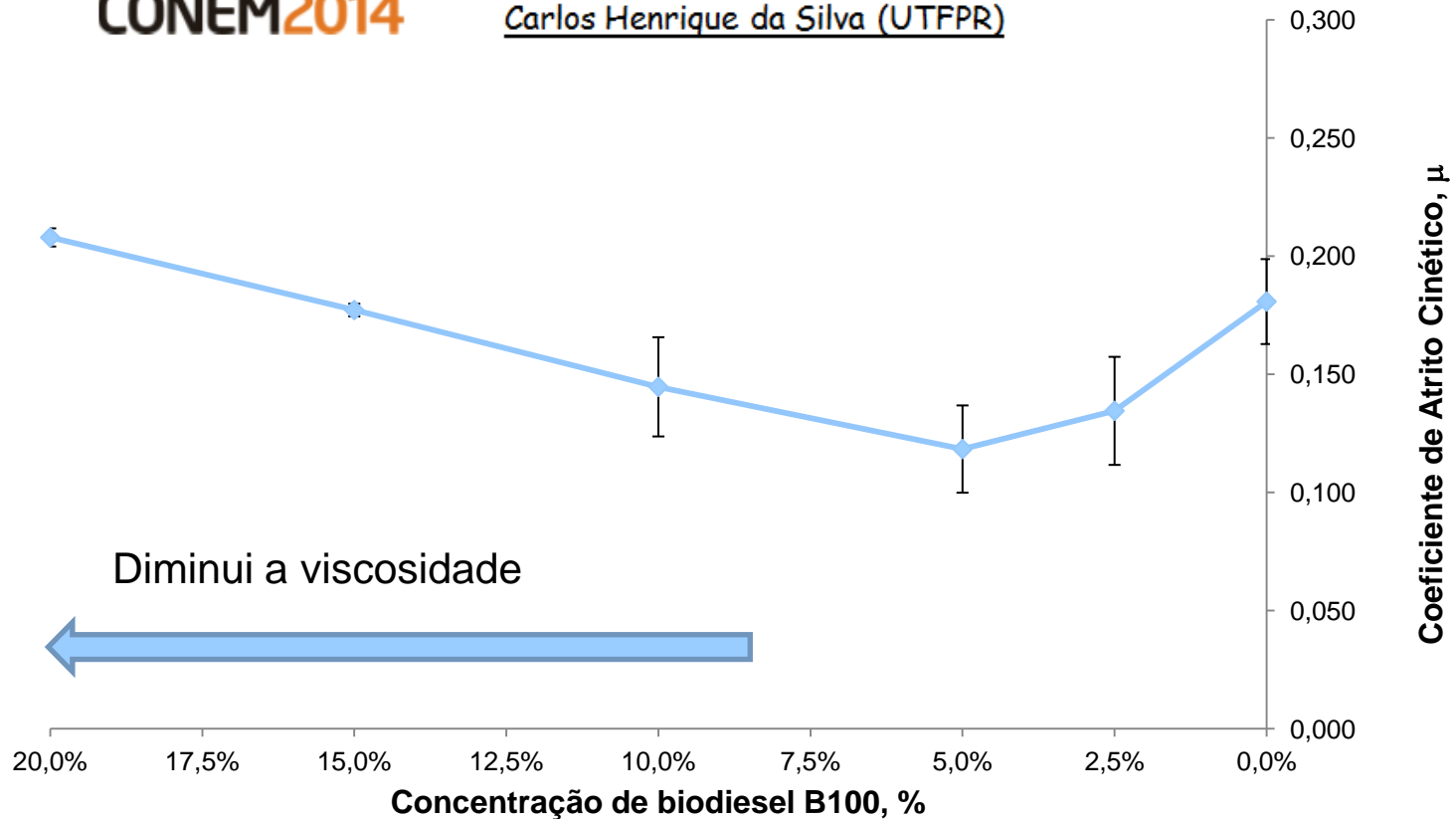


ESTUDO DA VARIAÇÃO DO ATRITO CINÉTICO EM MANCAIS DE DESLIZAMENTO DEVIDO À CONTAMINAÇÃO DO FLUIDO LUBRIFICANTE POR BIODIESEL



Bruno Chiuratto Salamone (UTFPR)
Ivo Artur Strano (UTFPR)
Carlos Henrique da Silva (UTFPR)

SAE 15W-40

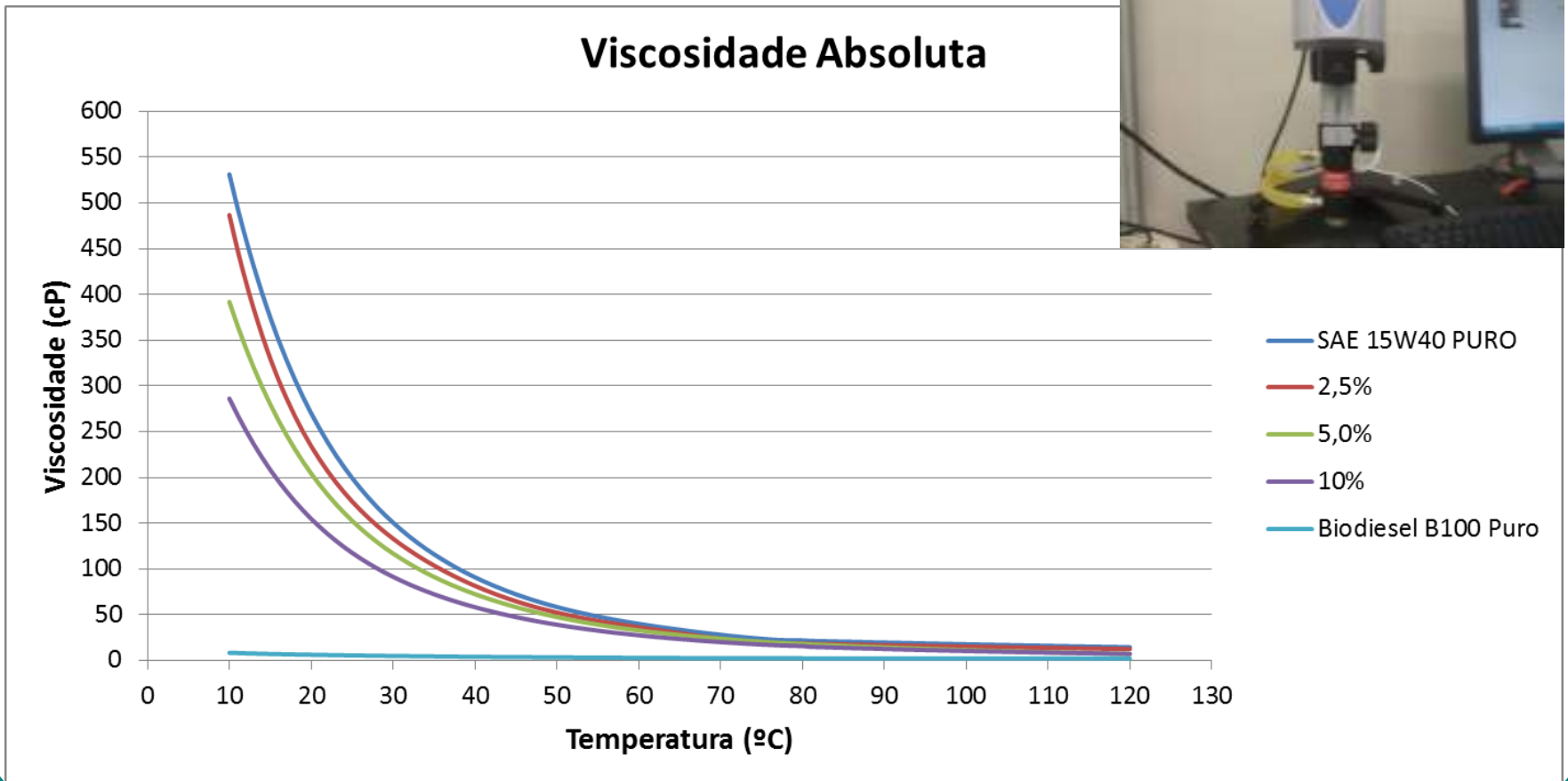


LUBRIFICANTE E CONTAMINAÇÃO

Viscosímetro Brookfield DV-II+ Pro



Viscosidade Absoluta

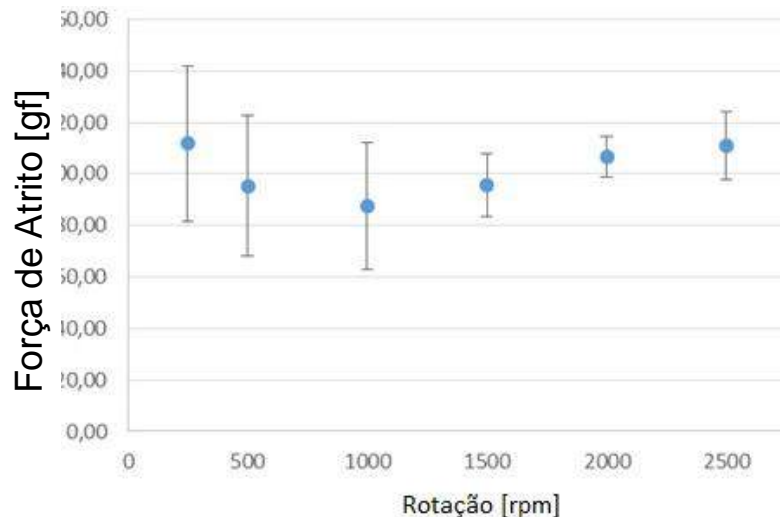


TCC: Alexandre Shimni e Rahael Maximiano

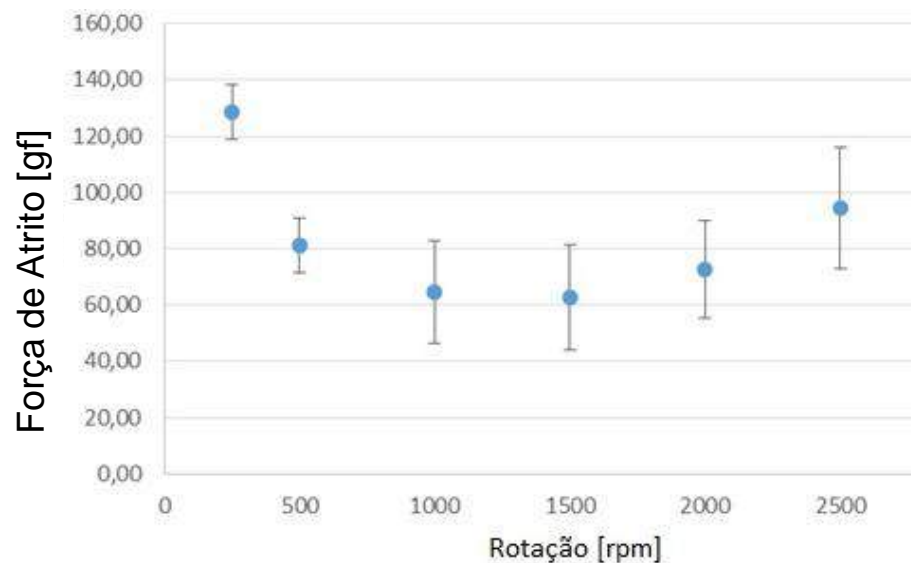
LUBRIFICANTE PURO

Estudo do efeito da carga na curva de Stribeck

$$\frac{r}{c} f = \phi \left[\left(\frac{r}{c} \right)^2 \frac{\mu N}{P} \right]$$



Força Normal = 709,91 gf

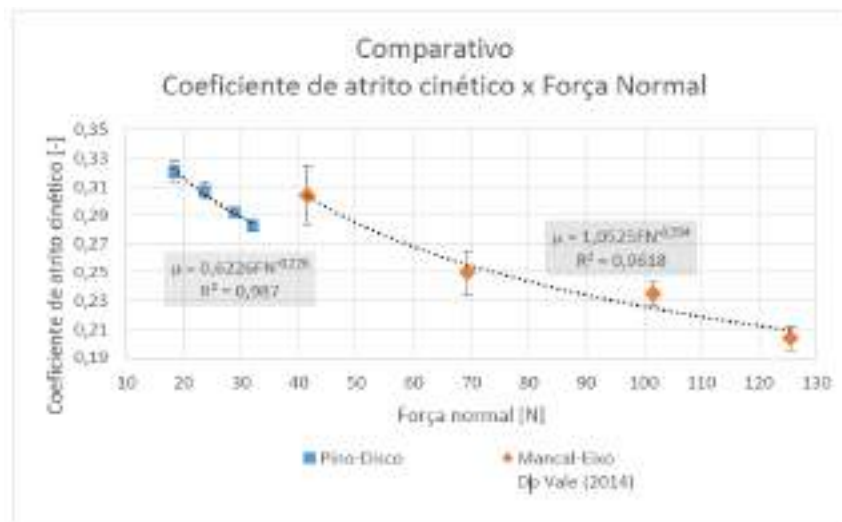
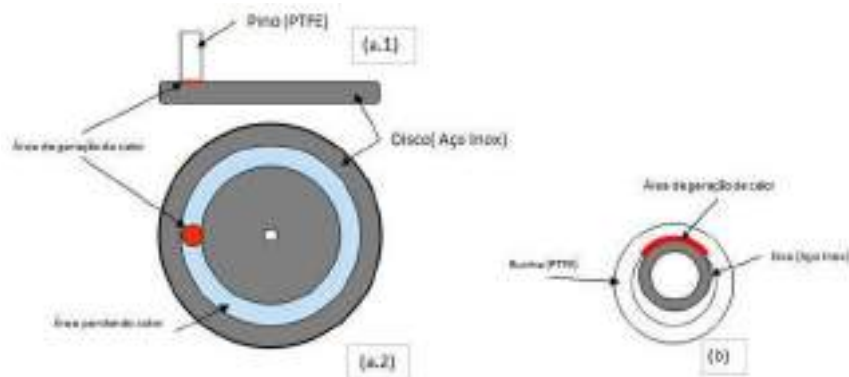
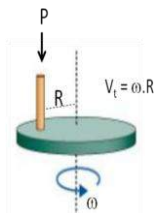


Força Normal = 1970 gf

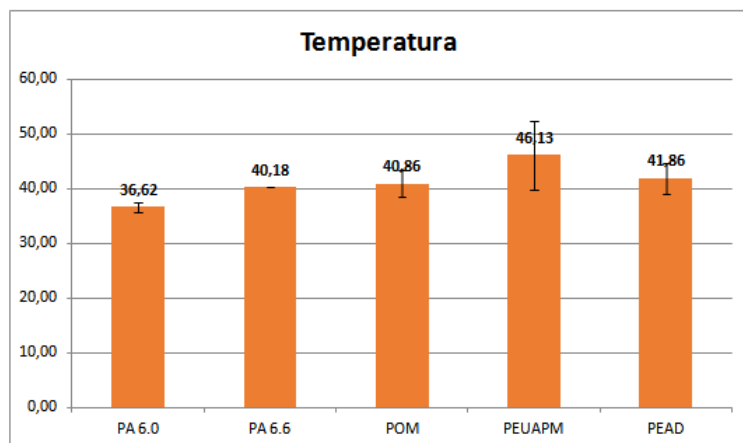
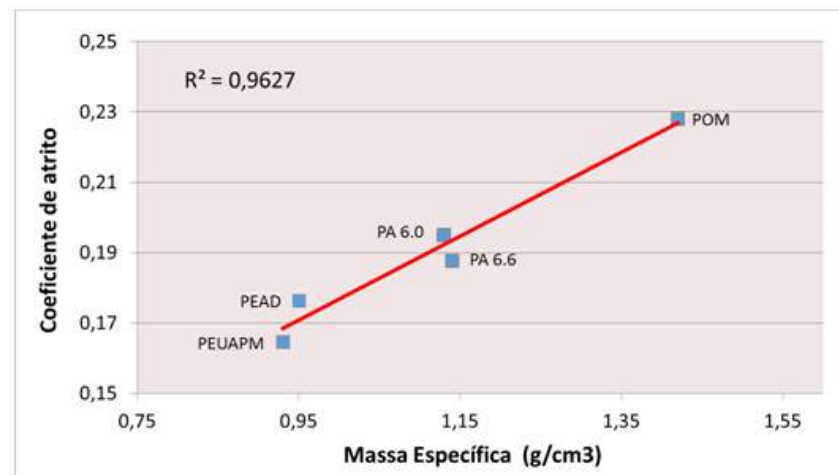
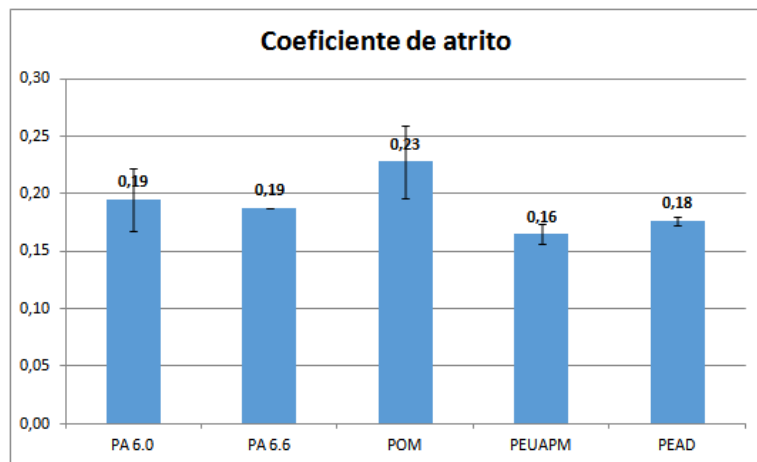
SAE 15W-40

TCC: AVALIAÇÃO DO COMPORTAMENTO TRIBOLÓGICO DO POLITETRAFLUORETILENO CONTRA AÇO INOXIDÁVEL SEM LUBRIFICAÇÃO EM ENSAIO PINO SOBRE DISCO

- **Alunos:** FELIPE FERNANDO BOUTIN + LUCAS PRADO CAETANO ROCHA - 2015
- **ORIENTADORES:** JOÃO L. DO VALE, CARLOS HENRIQUE DA SILVA



- TCC: **Estudo Do Comportamento Tribológico De Polímeros De Engenharia Em Deslizamento Sem Lubrificação Contra Aço Inoxidável** (MATEUS BOBECK ISHIDA +MATHEUS TERPLAK BEÊ) - 2015
- ORIENTADORES: JOÃO L. DO VALE, CARLOS HENRIQUE DA SILVA



Coefficiente dimensional de Archard

Material	Coefficiente dimensional de Archard (k) $\times 10^{-14}$ [m ³ /(N.m)]
PA 6.0	6,39 ± 0,00
PA 6.6	6,53 ± 0,00
POM	4,74 ± 0,00
PEUAPM	8,09 ± 0,00
PEAD	7,75 ± 0,00



2014-36-0145

Statistical analysis of kinetic friction coefficient for dry sliding plain bearing on shaft test of Polytetrafluoroethylene

$$t_{calc} = \frac{\bar{x}_1 - \bar{x}_2}{S_c \sqrt{\frac{n_1+n_2}{n_1 \cdot n_2}}}$$

$$S_c = \sqrt{\frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2}}$$

João Luiz do Vale
Carlos Henrique da Silva
Federal University of Technology – Paraná (UTFPR)

Variables	Condition 1	Condition 2	Condition 3	Condition 4
Test duration [min]		120		
Normal force [N]	41.5	69.3	101.6	125.5
Contact half width [mm]	1.79	2.32	2.80	3.12
Sliding velocity [m/s]	0.84	0.65	0.54	0.48
Mean pressure [MPa]	0.58	0.75	0.91	1.01
Mean PV condition [MPa.m.s ⁻¹]		0,49		

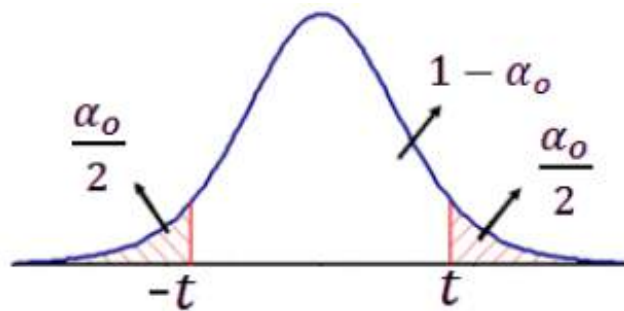


Figure 5. Probability Density Function for two-tailed Student test.

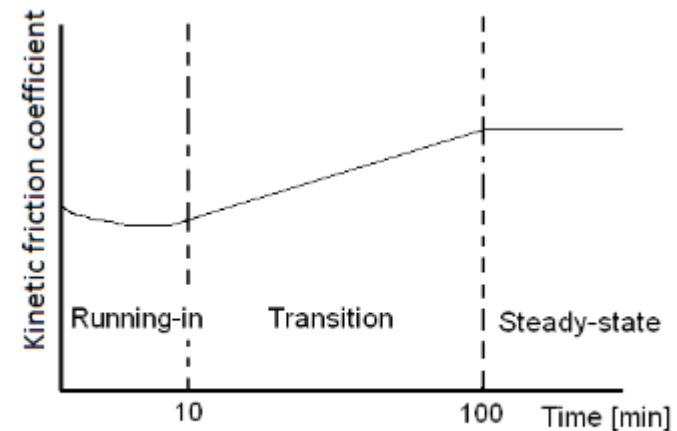
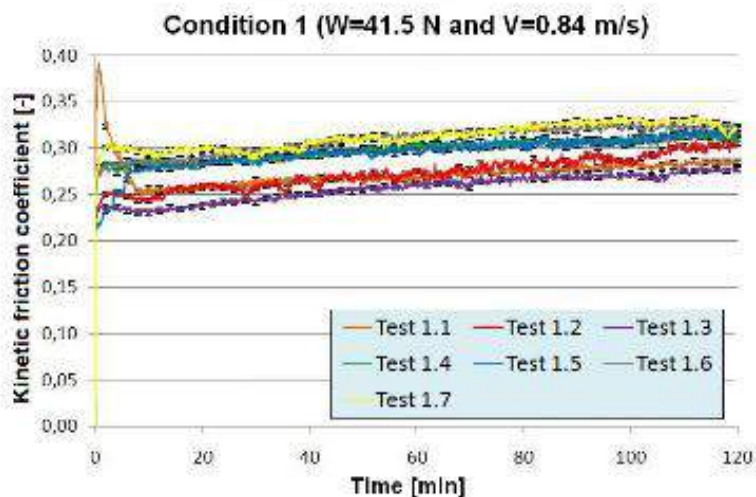


Figure 6. Schematic representation of the typical behavior of the kinetic friction coefficient as time function.

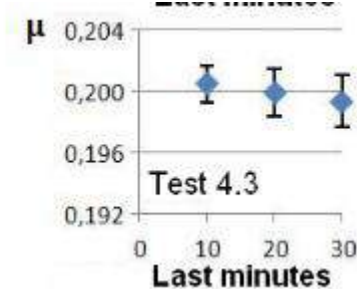
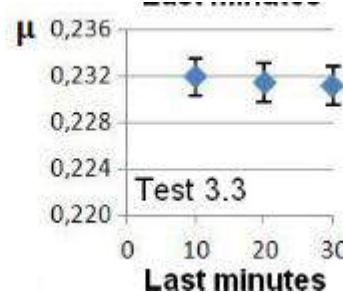
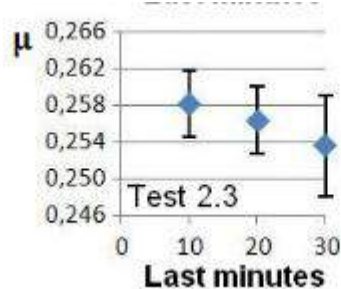
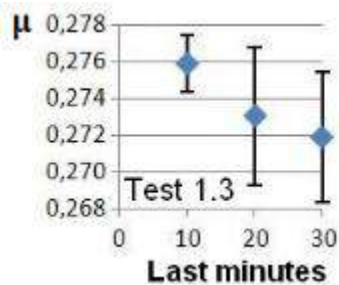
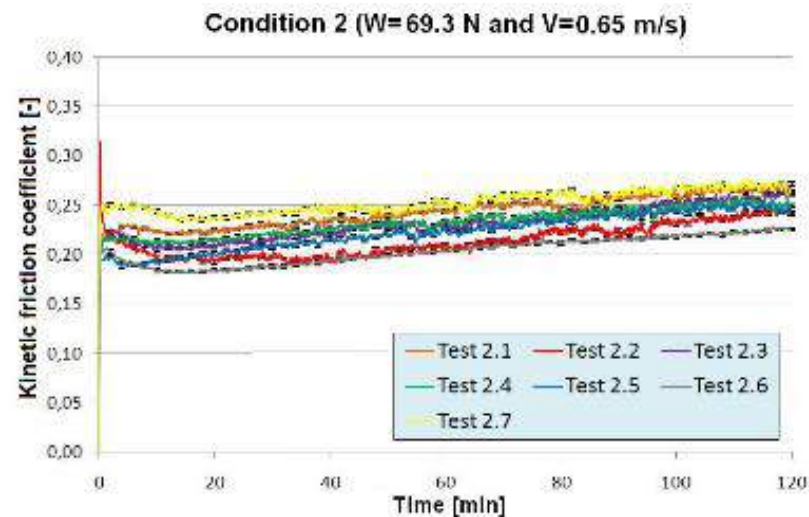


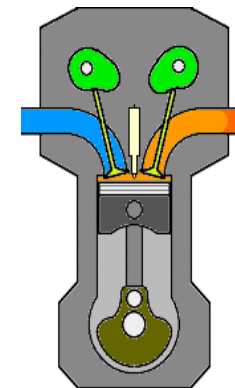
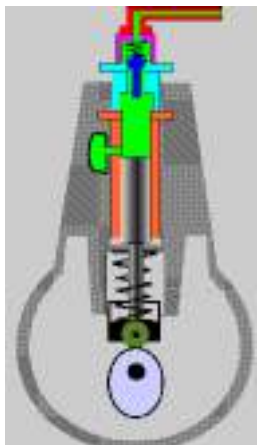
2014-36-0145

Statistical analysis of kinetic friction coefficient for dry sliding plain bearing on shaft test of Polytetrafluoroethylene



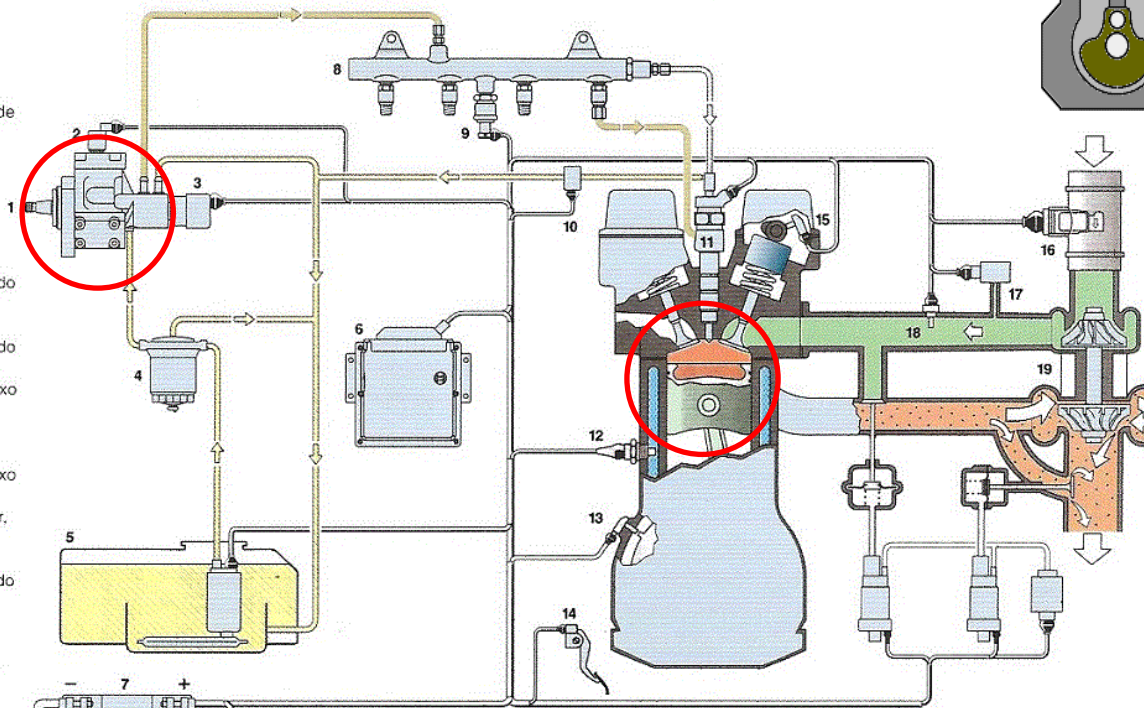
(b)





Sensores de um sistema de injeção com Common Rail e diversos componentes do sistema.

- 1 bomba de alta pressão.
- 2 válvula de desativação do elemento.
- 3 válvula reguladora de pressão.
- 4 filtro de combustível.
- 5 tanque de combustível com pré-filtro e bomba de pré-alimentação.
- 6 unidade de comando.
- 7 bateria.
- 8 acumulador de alta pressão (Rail).
- 9 sensor de pressão do Rail.
- 10 sensor de temperatura do combustível.
- 11 injetor.
- 12 sensor de temperatura do agente de refrigeração.
- 13 sensor de rotação do eixo de manivela.
- 14 sensor do pedal do acelerador.
- 15 sensor de rotação do eixo de comando.
- 16 medidor de massa de ar.
- 17 sensor de pressão de carga.
- 18 sensor de temperatura do ar aspirado.
- 19 turbocompressor.



BOSCH



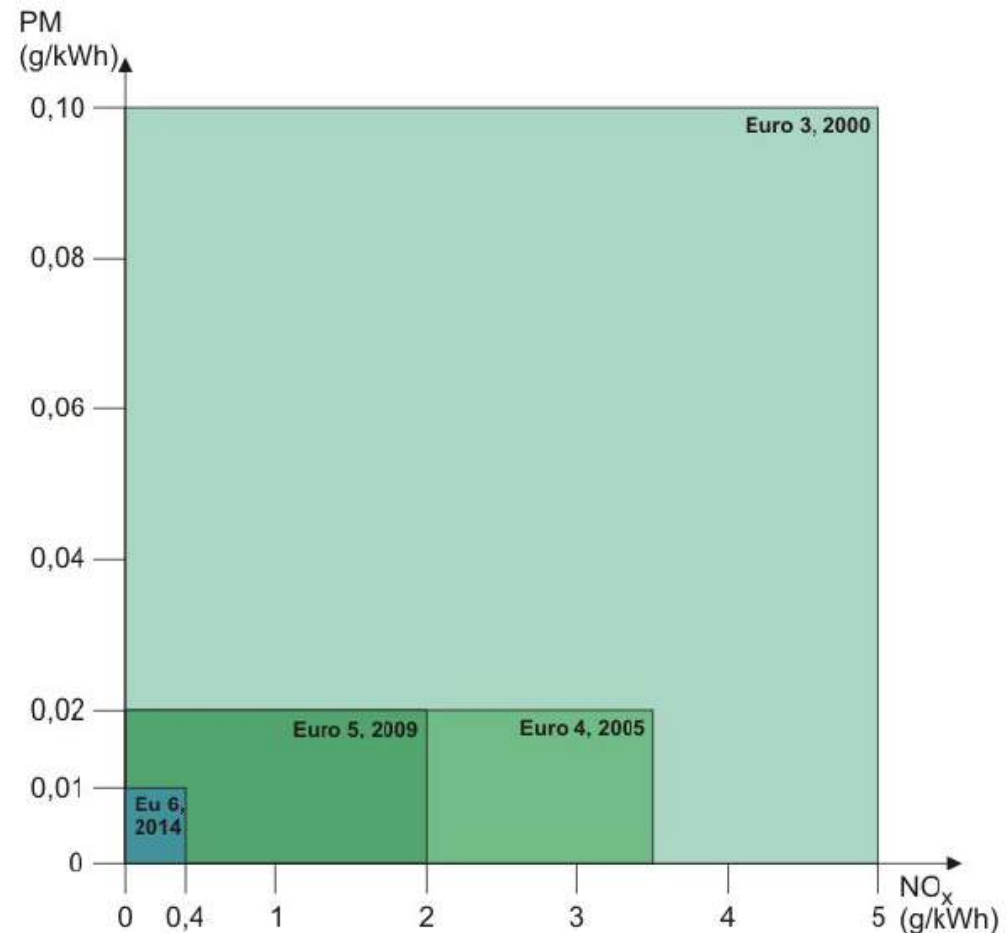
MAHLE

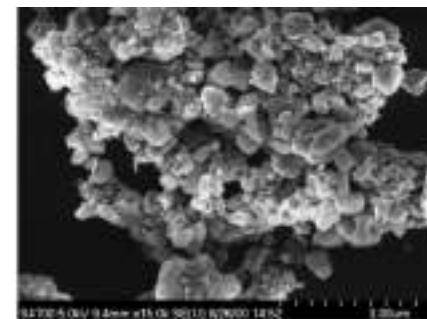
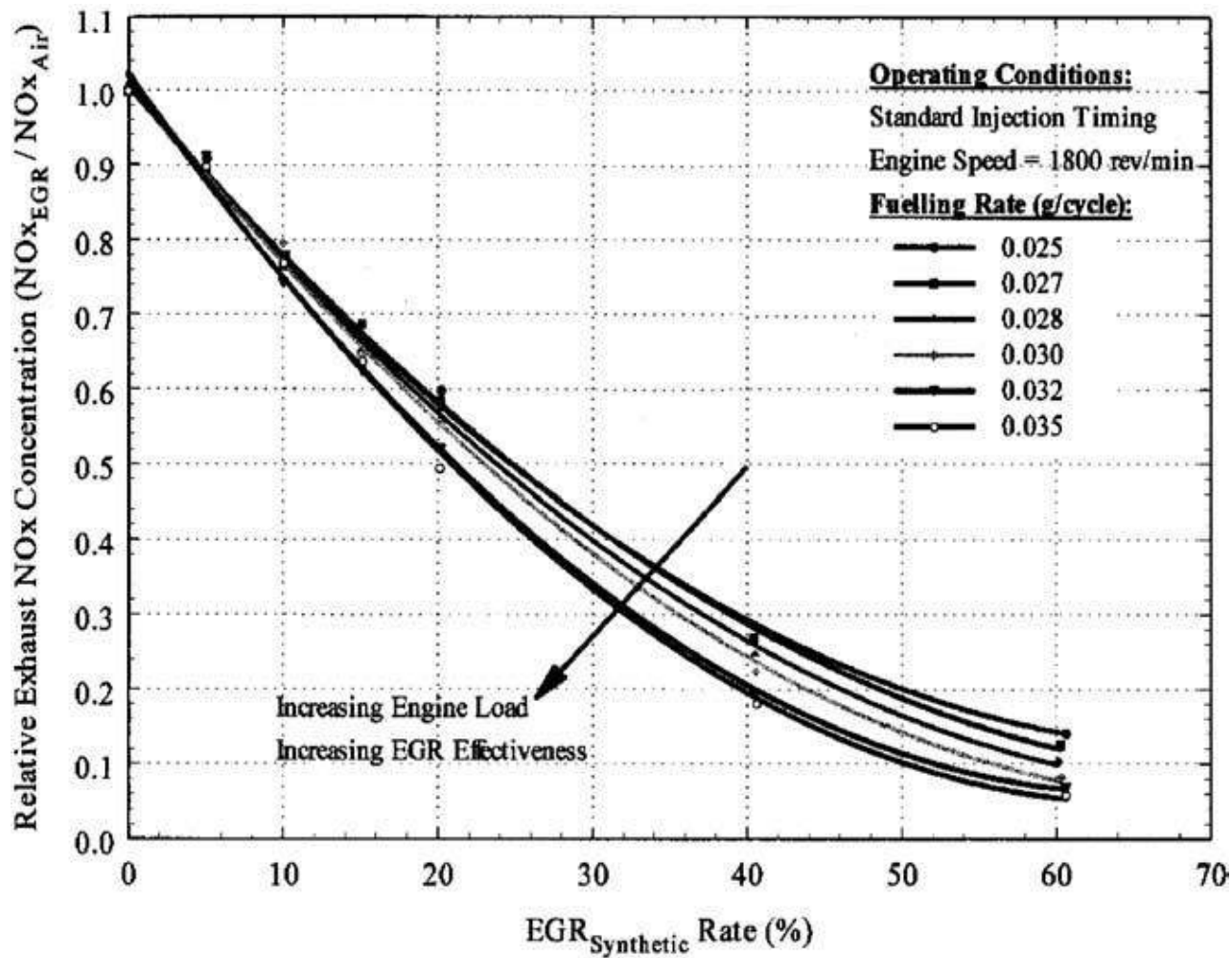


- Para atender aos níveis de emissão impostos pelas regulamentações, novas tecnologias e sistemas vem sendo desenvolvidos.

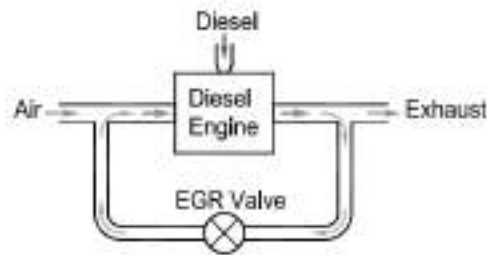
- **EGR** (*Exhaust Gas Recirculation*)
- **DPF** (*Diesel Particulate Filter*)
- **SCR** (*Selective Catalytic Reduction*)

EGR: Diminui a temperatura de combustão e reduz a concentração de oxigênio do fluido de trabalho que é admitido na câmara de combustão, reduzindo dessa forma a formação de NO_x (ZHENG, 2004).





- Motor Diesel x EGR x Análise de óleo



$$EGR_{ratio} = \frac{[\%]Exaustão}{[\%]Exaustão + [\%]Ar_{puro}}$$

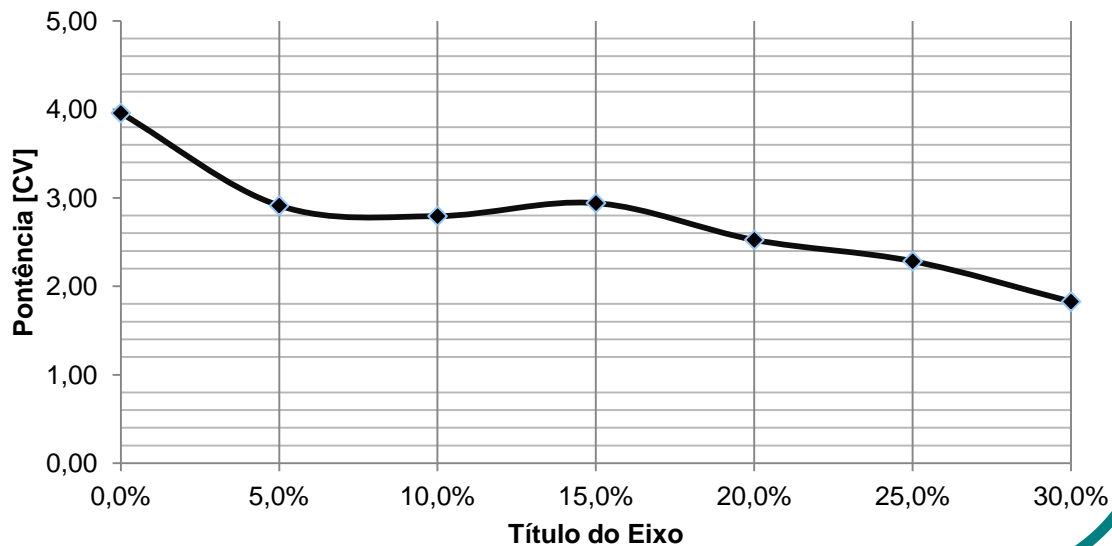
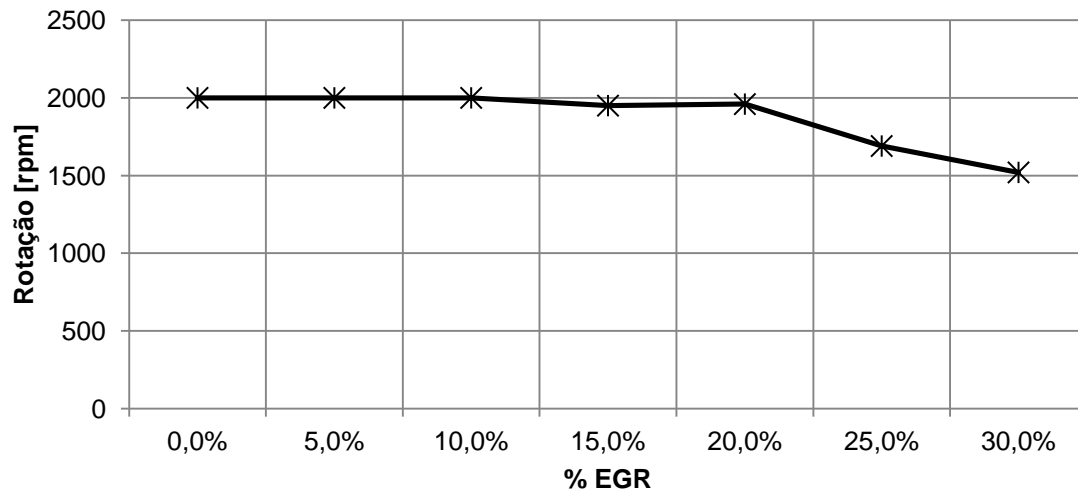


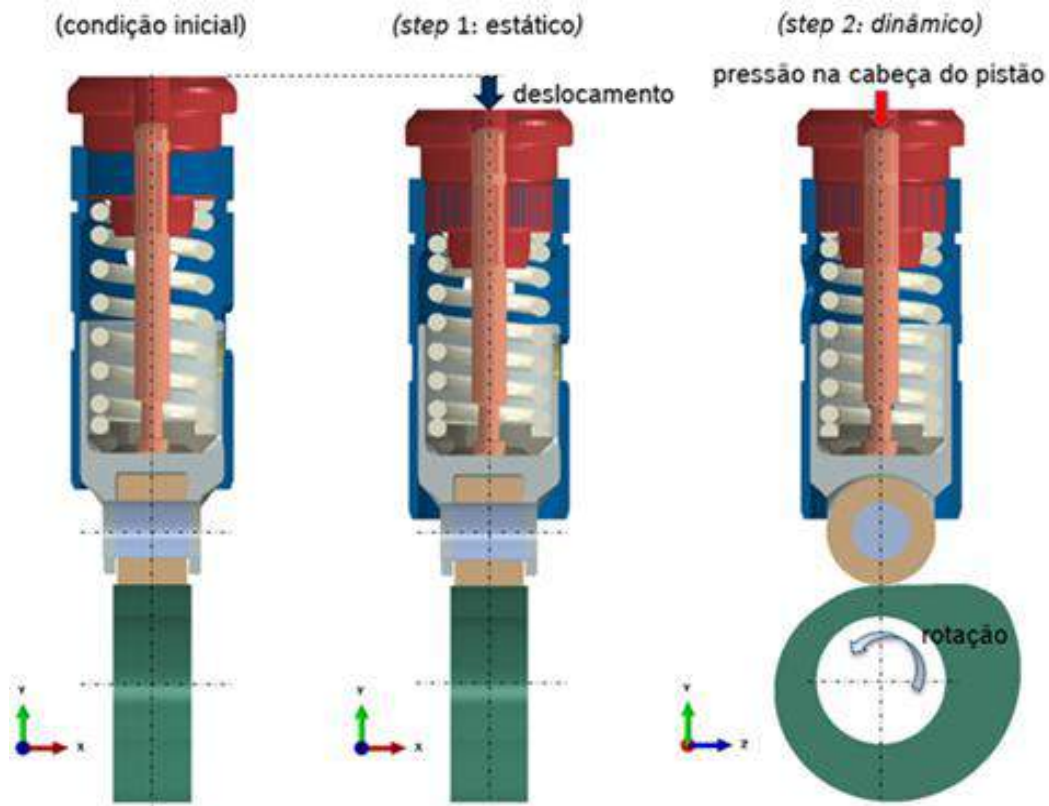
- Motor monocilindro – 4CV
- Modelo Yanmar B7
- Combustível: Diesel
- Pistão com 5 Anéis
- Óleo Lubrificante 15W40

ANÁLISE DE ÓLEO

- Viscosidade
- Oxidação
- TAN
- Contaminação por água
- Contagem de partículas
- Soot (Cinzas)

[EGR x Rotação Máxima]

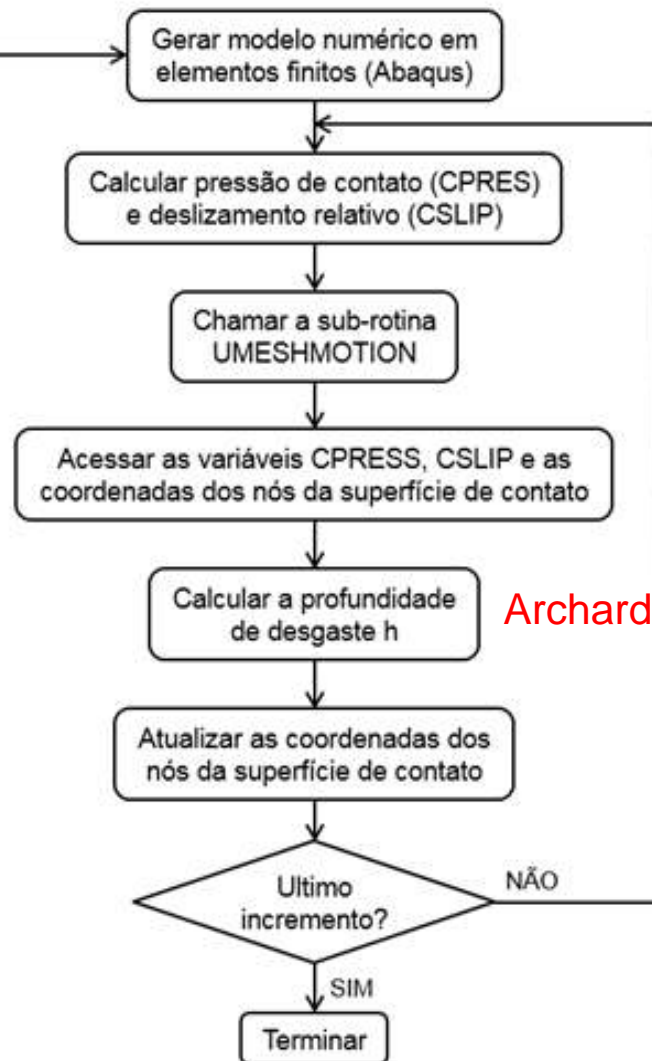


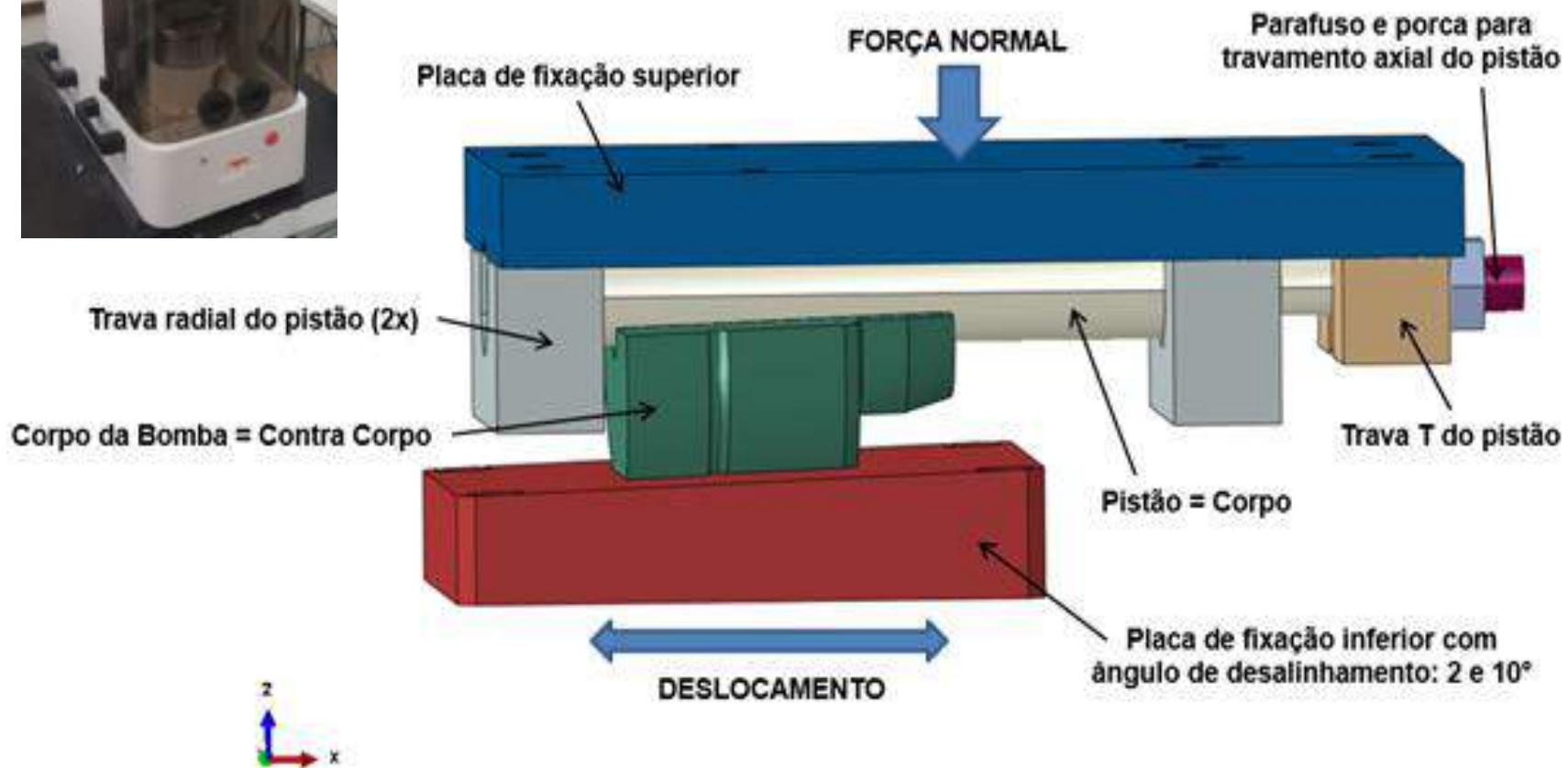


Metodologia da Análise Numérica

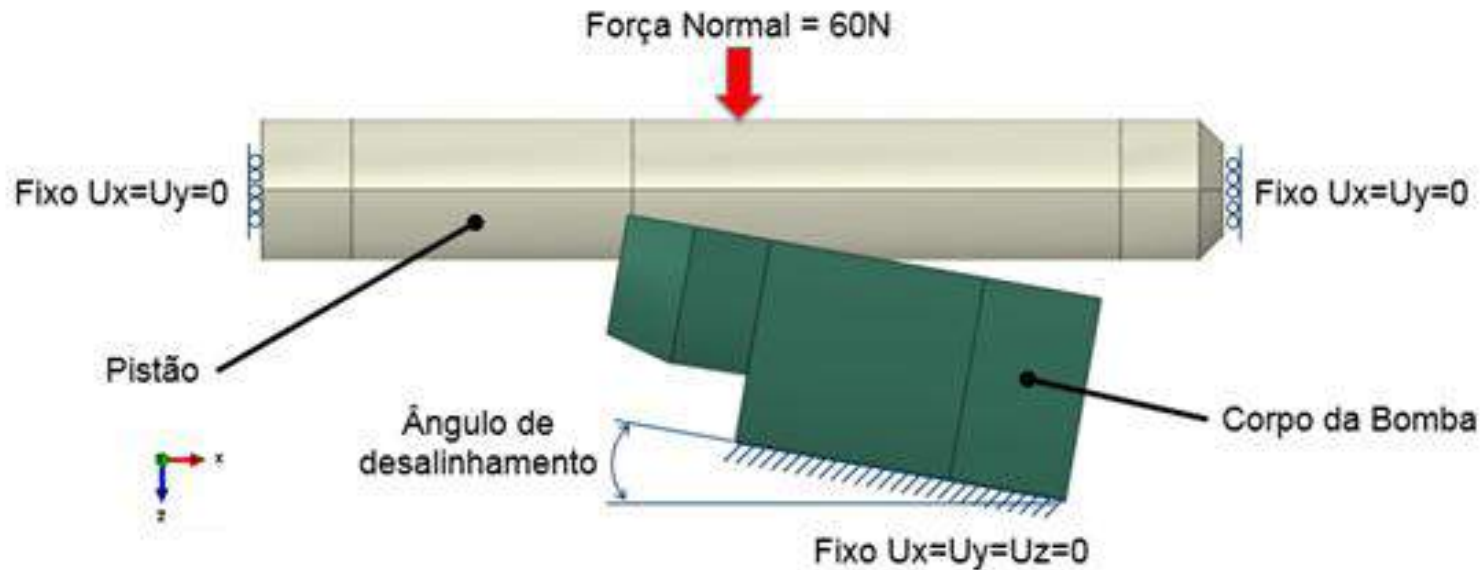
Parâmetros de entrada:

- Geometrias
- Propriedades dos materiais
- Carregamento / Forças
- Condições de contorno / Deslocamentos
- Coeficiente de atrito
- Coeficiente de desgaste
- Numero de ciclos





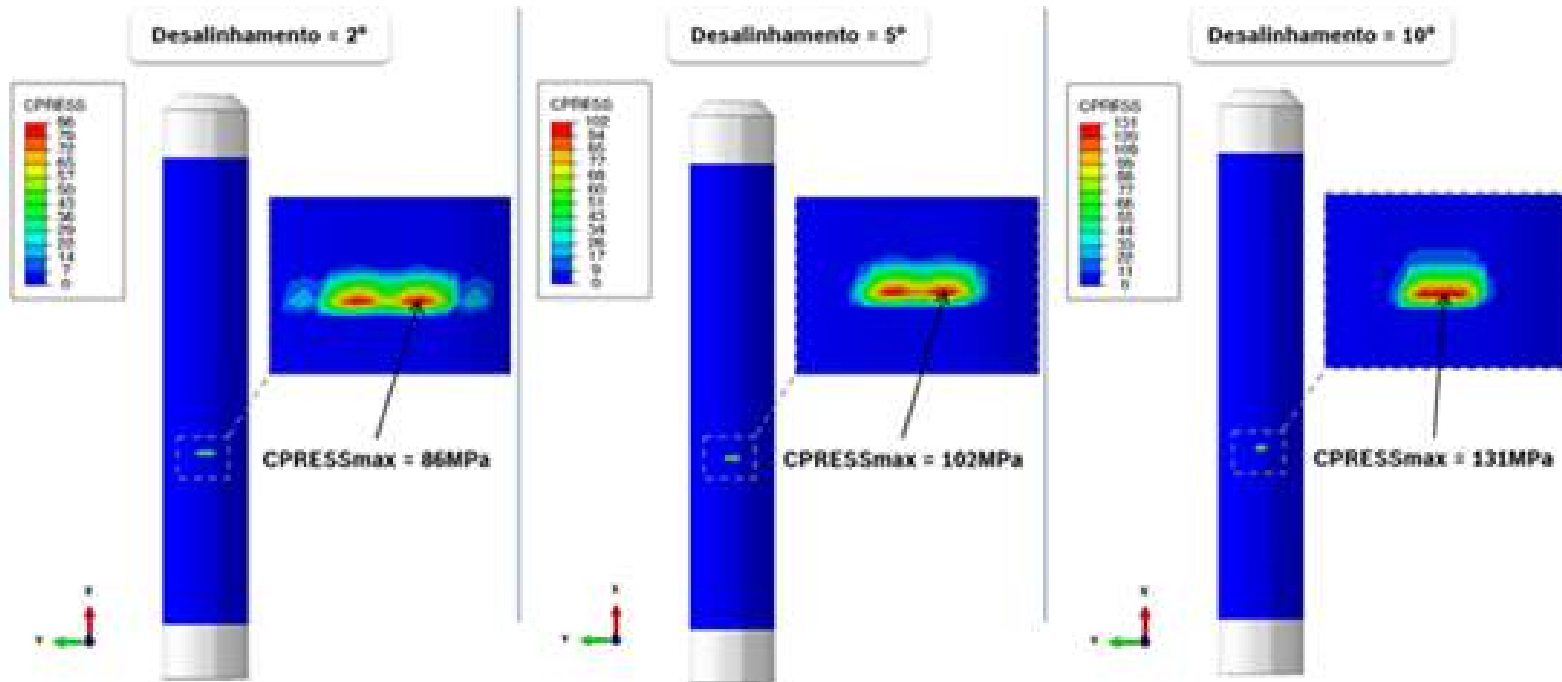
Bomba de Combustível: Pistão x Cilindro



Modelo numérico do dispositivo de teste de desgaste.

Desalinhamentos: 2°, 5° e 10°

Ensaio: a seco



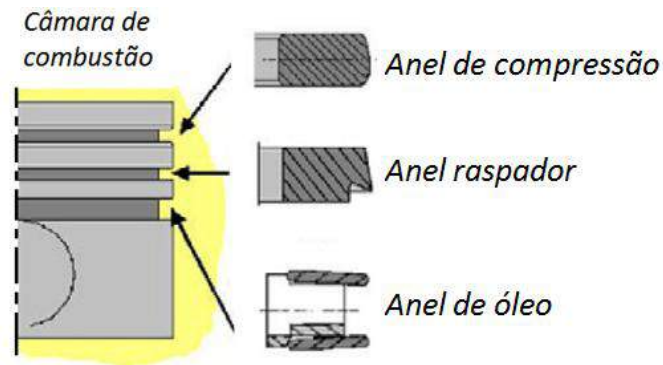
Varição da tensão de contato com o ângulo de desalinhamento, para força normal de 60N.

● **INFLUÊNCIA DA MICROESTRUTURA DE FERROS FUNDIDOS NA OCORRÊNCIA DE *FOLDED METAL* E NO COEFICIENTE DE ATRITO EM SUPERFÍCIES BRUNIDAS**

Aluno: João Luiz do Vale

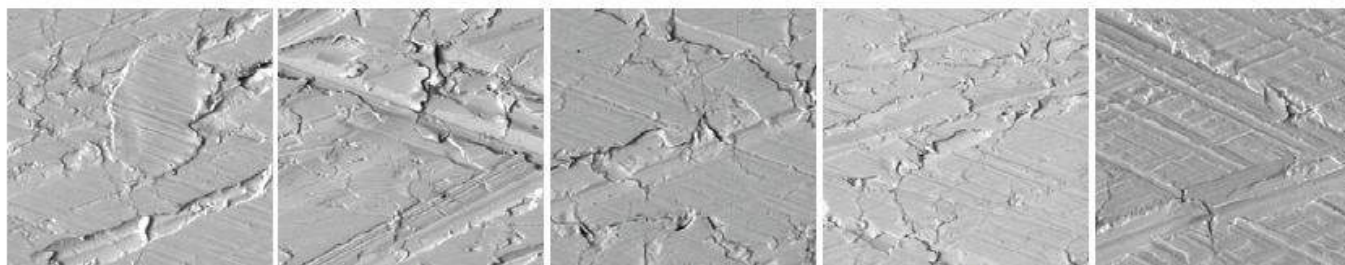
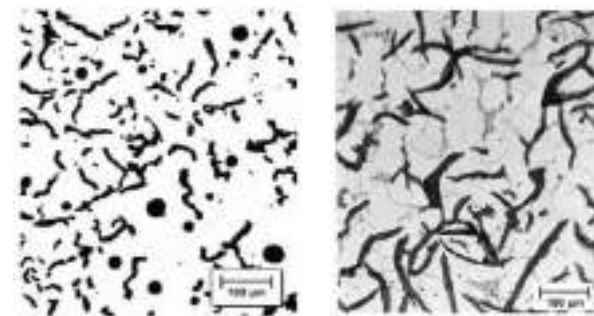
Orientador: Giuseppe Pintaúde

Co-orientador: Carlos Henrique da Silva



Folded metal:

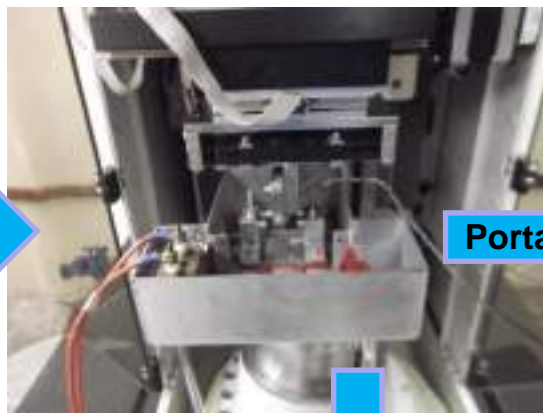
- Porções de material dobrado que cobrem os sulcos;
- Causado por deformação plástica;



(1) Seriamente defeituosa → (2) → (3) → (4) → (5) Levemente defeituosa



Adaptação



Porta-anel

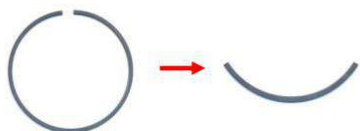


Anel

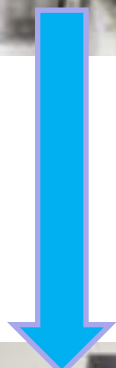


Termopares de controle e monitoramento

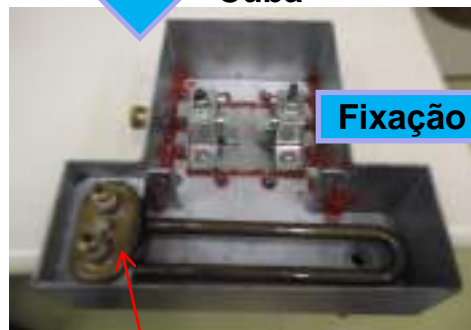
Fluxograma para preparação das amostras



Tempo de ensaio [s]	65
Temperatura do óleo [°C]	40



Cuba

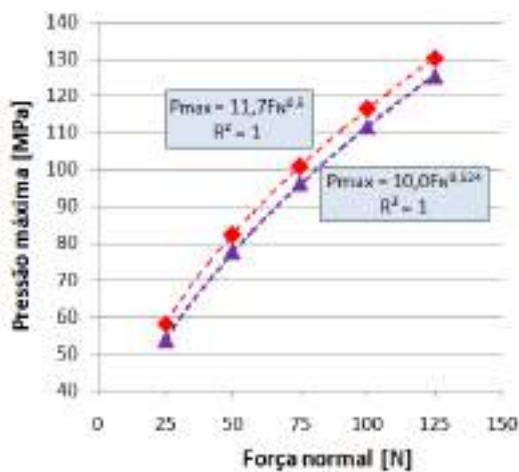
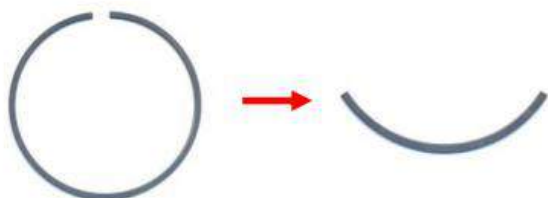


Resistor

Fixação amostra



Amostra do **CILINDRO**

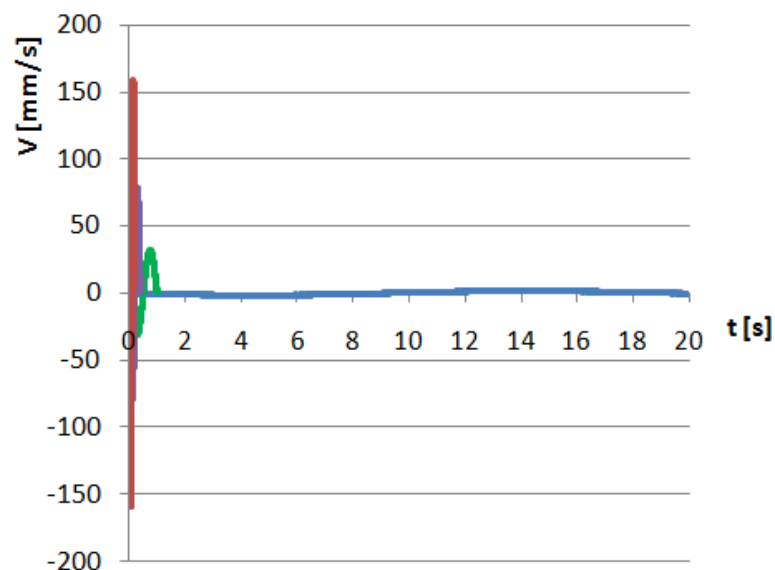
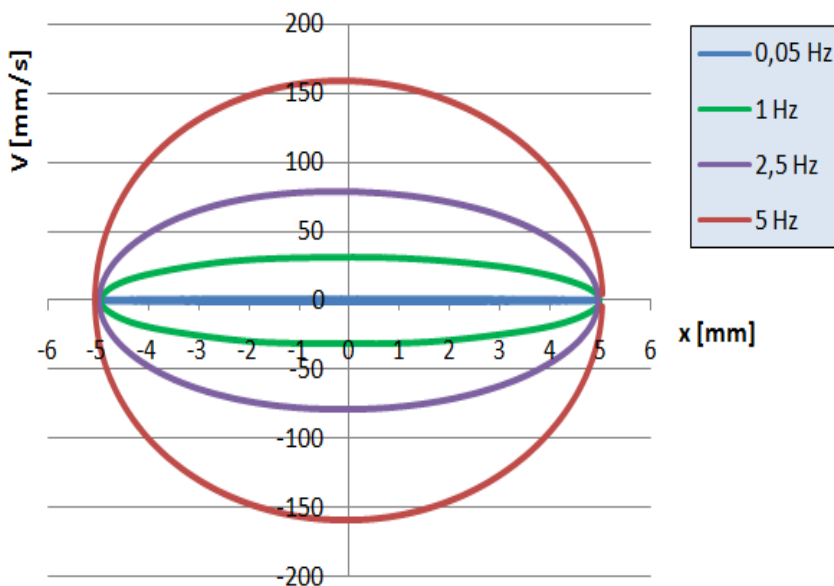


Parâmetros	Valores															
Condição	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Força normal [N]	25	50	75	100	25	50	75	100	25	50	75	100	25	50	75	100
Frequência [Hz]	0,05				1				2,5				5			
Comprimento de pista [mm]	10															

Grande variação de frequência

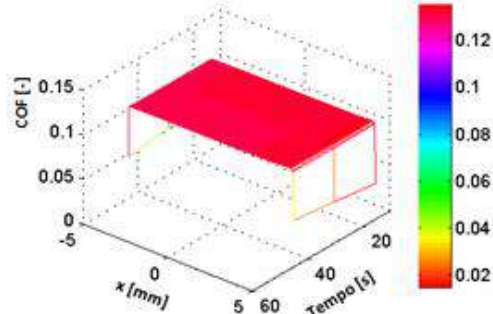
Constante

Planejamento com condições favoráveis e não favoráveis à formação de filme

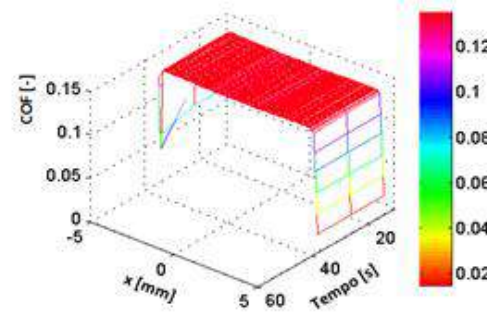


Triboscopia:

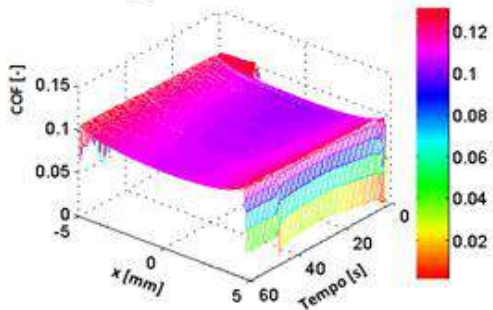
➤ FN = 25 e 100 N.



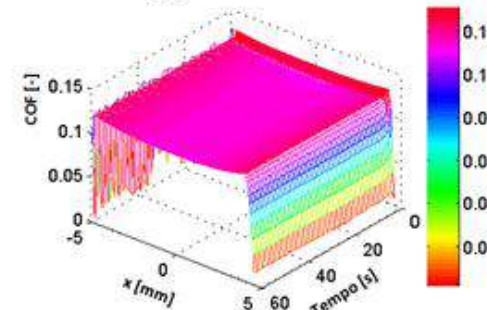
(a) 25 N – 0,05 Hz



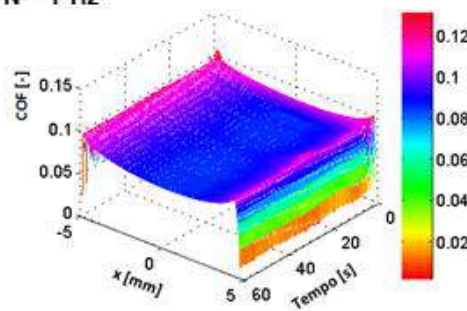
(b) 100 N – 0,05 Hz



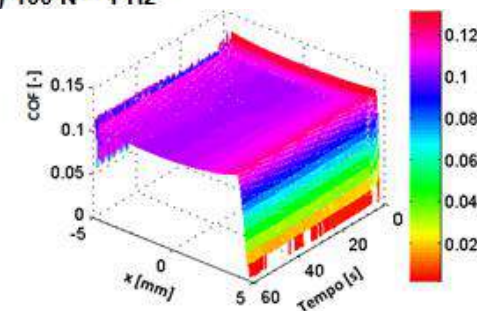
(c) 25 N – 1 Hz



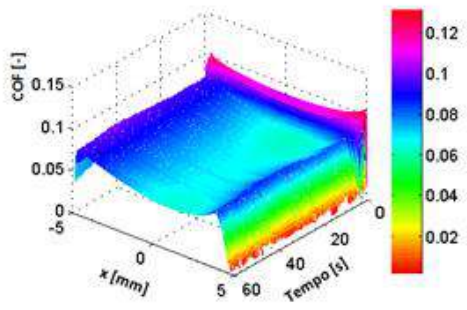
(d) 100 N – 1 Hz



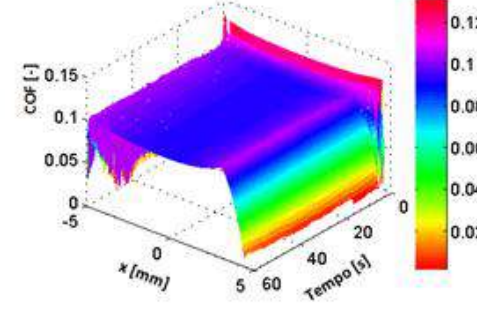
(e) 25 N – 2,5 Hz



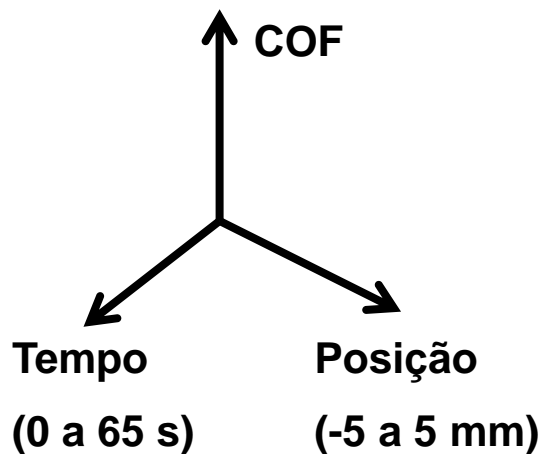
(f) 100 N – 2,5 Hz

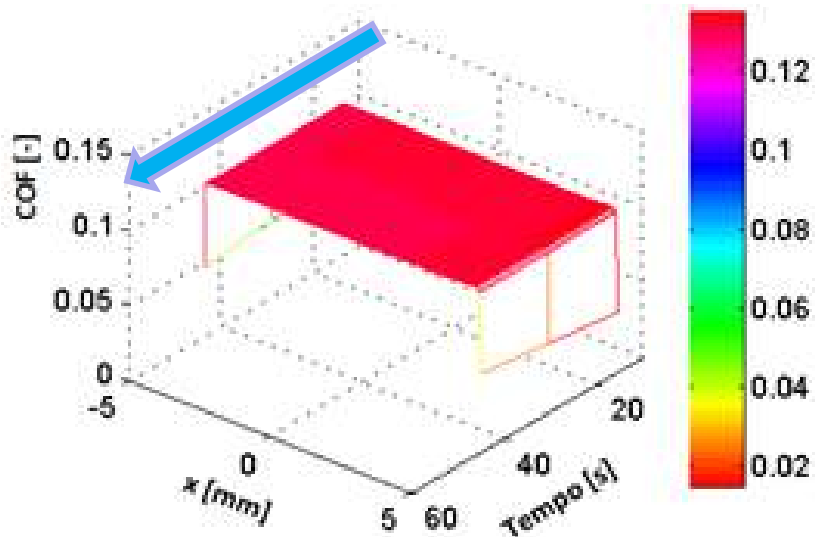


(g) 25 N – 5 Hz

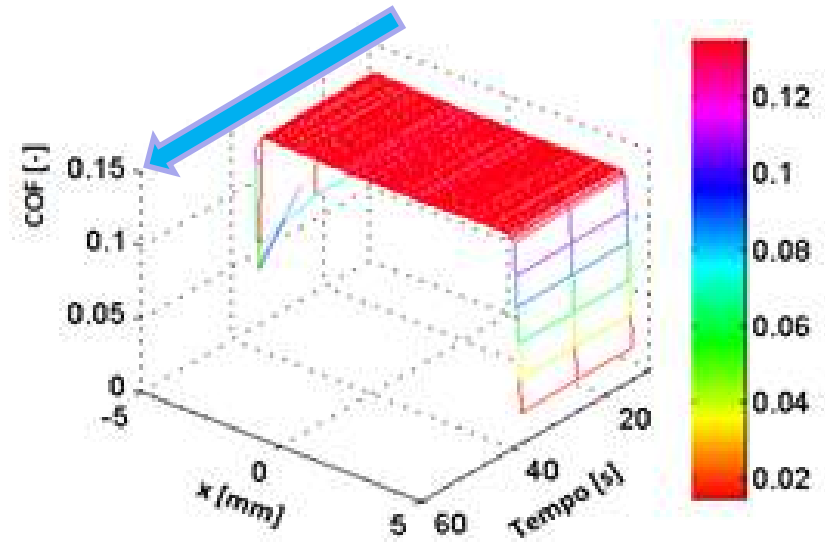


(h) 100 N – 5 Hz





(a) 25 N – 0,05 Hz

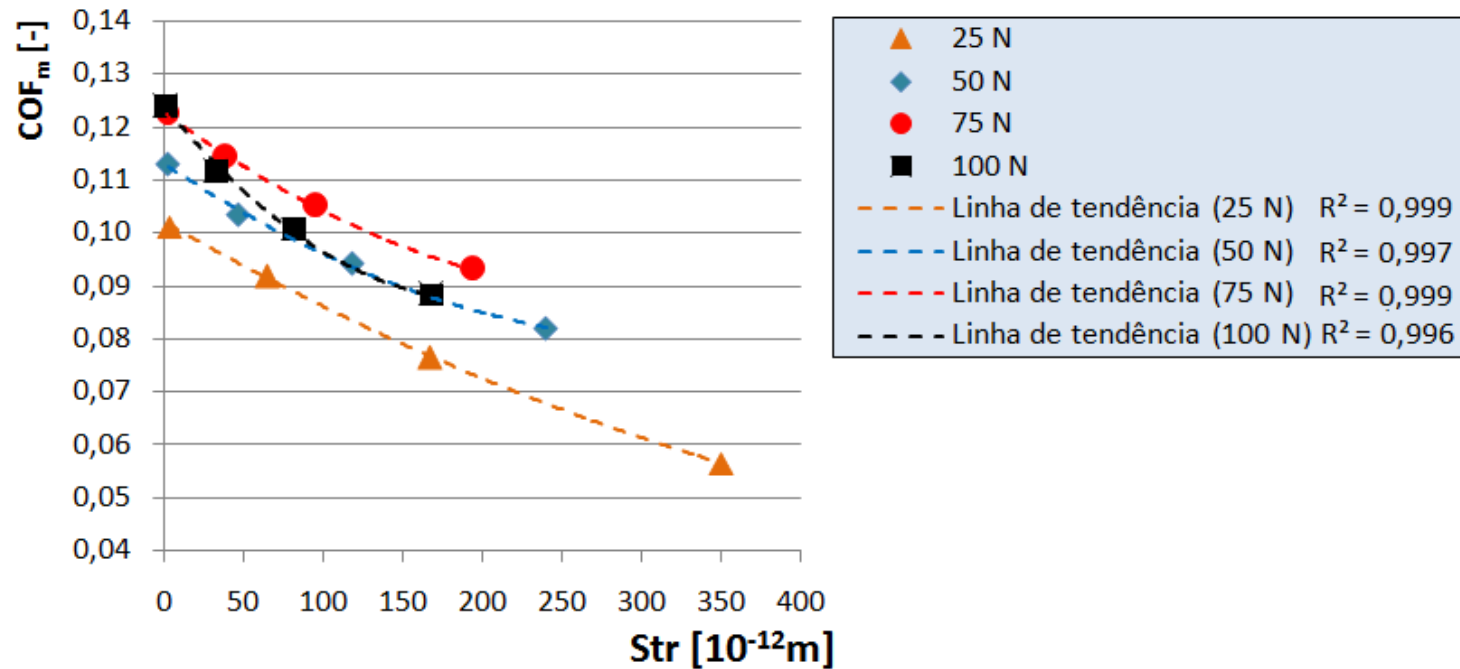


(b) 100 N – 0,05 Hz

➤ Para $f=0.05$ Hz

→ COF constante ao longo de todo ensaio;

→ Relação com a Força normal (aumento da área de contato real);



- ↓ Força normal → ↓ COF_m
- Altos valores de R² para as curvas
- Tendência de mesclagem das curvas para F_N > 50N

Subsistemas:
**Geometria x
Carregamento**

Ensaio bancada:
**Montagem x
Aquisição de
dados**

**Elementos
de
Máquina**

Análise Numérica:
**Tensão x Mecânica
da Superfície x
Desgaste**

Análises Químicas:
**Debris x Óleo
Lubrificante**

Obrigado