# REVESTIMENTOS MULTIFUNCIONAIS A BASE DE CARBONO APLICADOS EM COMPRESSORES HERMÉTICOS SEM ÓLEO.


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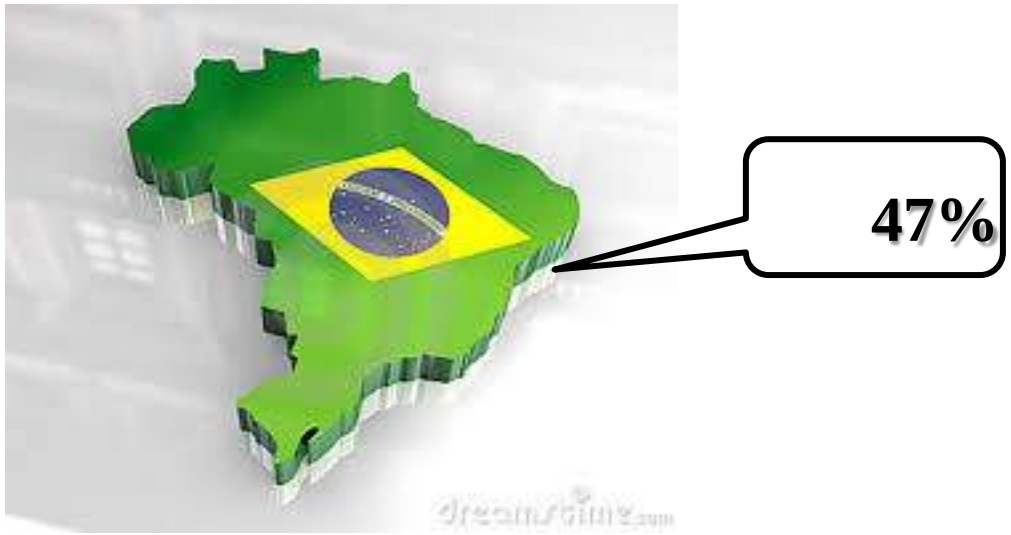
# *Hermetic compressor??*

# Refrigeration: Home energy consumption

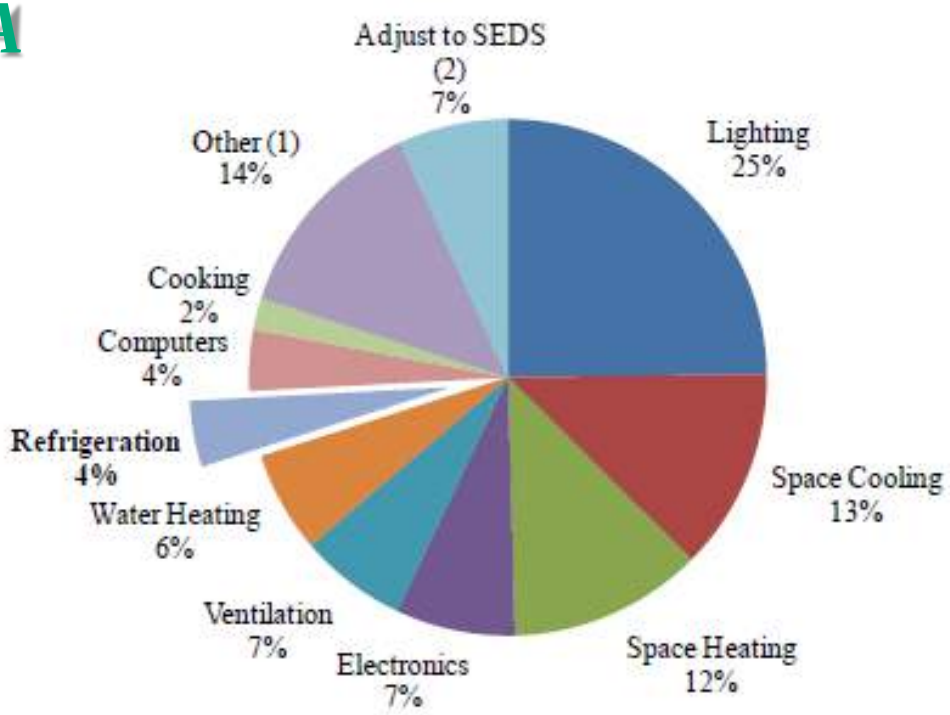

*United States Environmental Protection Agency, Partnerships for Home Energy Efficiency Report*




*Programa Nacional de Conservação de Energia Elétrica, Pesquisa de Posse de Equipamentos e Hábitos de Uso – Ano Base 2005, Classe Residencial, Relatório Brasil*

# Refrigeration: Commercial energy consumption

## USA




Source: DOE 2008a

***Commercial energy consumption = 0.719 Quad = 208.24 GWh***

Navigant Consulting Inc, *Energy savings potential and R&D opportunities for commercial refrigeration – Final Report, September 2009, 211 pages.*

***Any improvement in the efficiency of the hermetic compressor may have a substantial impact on the global energy balance and, as a consequence, on the environment.***

- *The refrigeration industry has moved on from CFC based refrigerants such as R-12 to environmentally friendly HFC based refrigerants like R134a and more recently to the harmless isobutene R600a.*

| Refrigerant | Life Time (years) | ODP | HGWP | Toxicity | Air Flammability | |
|---|---|---|---|---|---|---|
| | | | | | LEL | UEL |
| | | | | | Volume % | |
| CFC R12 | 120 | 1 | 7100 | TLV= 1000ppm | Not flammable | |
| HCFC R22 | 15 | < 1 | 1500 | - | - | |
| HFCR 134a | 16 | 0 | 3200 | AEL= 1000 ppm | Not flammable | |
| Propane R230 | Months | 0 | < 5 | Low | 2.1 | 9.5 |
| Butane R600 | Weeks | 0 | < 5 | Slightly anaesthetic - TLV= 800ppm | 1.8 | 8.5 |
| Isobutane R600a | < 1 Week | 0 | <0.01 | Slightly anaesthetic - TLV= ND | 1.8 | 8.5 |

*ODP = Ozone Depletion Potential - HGWP = Halocarbon Global Warming Potential - TLV= Threshold limit value*
*AEL = Acceptable exposure limit - LEL = Lower explosive limit - UEL = Upper explosive limit*

- *Moreover, due to miscibility issues with HFC refrigerants, the compressor lubricants have also changed from mineral type lubricant to synthetic polyolester (POE) and polyalkylene glycol (PAG) lubricants.*

# ARLTERNATIVE REFRIGERANT
# &
# ARLTERNATIVE LUBRICANTS

⇓

*Increase in severity of tribological contacts*

+

*Smaller clearances and increased speeds*

+

*Miscibility oil – refrigerant / insulation*

+

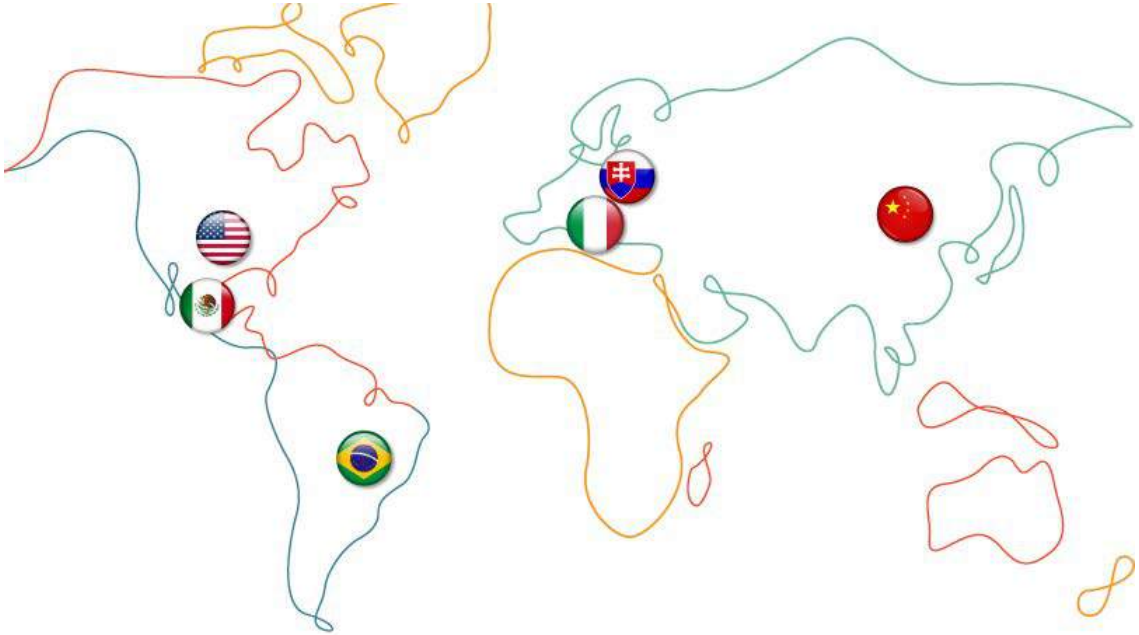
*Limited lubrication: boundary and mixed lubrication regimes*

⇓

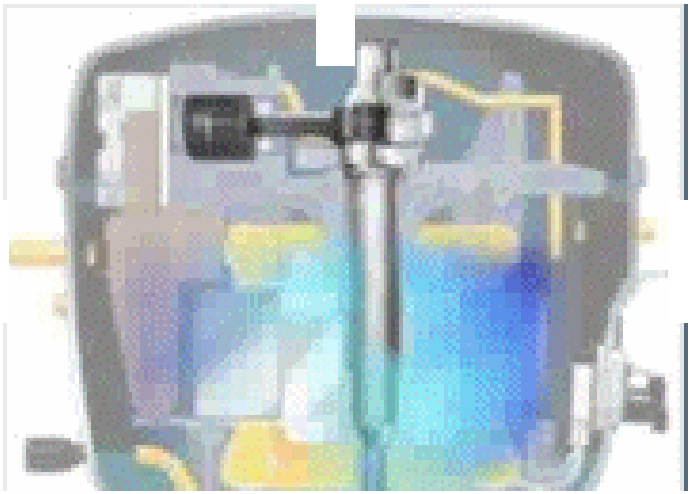
# TOWARDS OIL-LESS COMPRESSORS

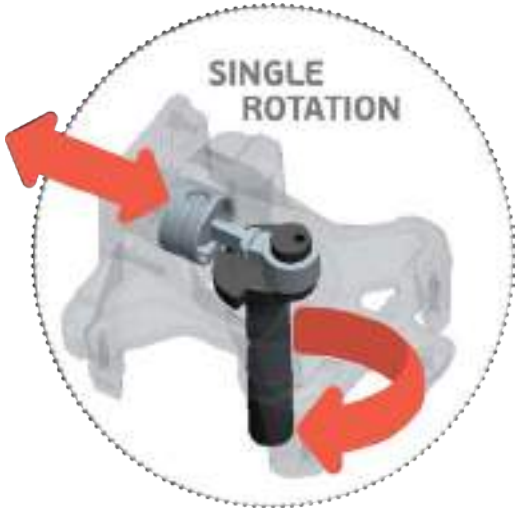
# SOLID LUBRICATION AND SOLID LUBRICANTS

# *Whirlpool-Embraco: Brazilian Compressor Company*



- *Factories in 5 countries*
- *38,000,00 compressors/year*
- *1+ compressor/second*
- *23% global market share*
- *1/4 refrigerators worldwide uses Embraco compressors*
- *80 countries*
- *12000 direct employees*
- *500 people R&D*
- *Strong cooperation with Universities*



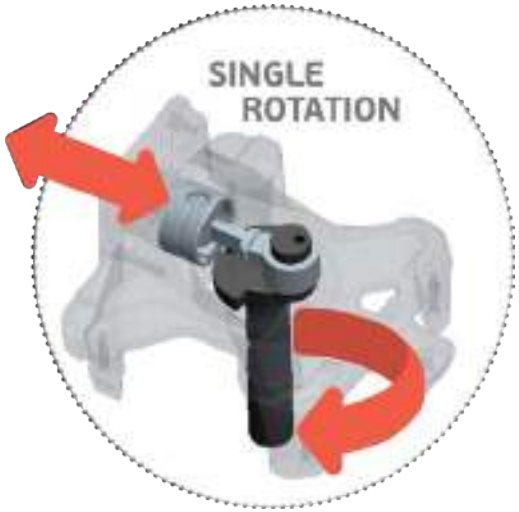



***High complexity***

- ***Life > 10 years (warranty)***
- ***Tidy tolerances***
- ***Oil viscosity: 5-10 Iso***

- ***On -off***
- ***Circular Motion***
- ***Single speed***
- ***Many tribological contacts***
- ***Oil for lubrication***

# Incremental

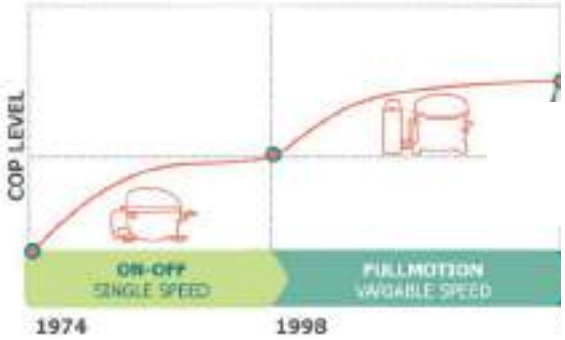



## 1974

- *On -off*
- *Circular Motion*
- ***Single speed***
- *Many tribological contacts*
- *Oil for lubricatic*

## 1998

- *Fullmotion®*
- *Circular Motion*
- ***Variable speed***
- *Many tribological contacts*
- *Oil for lubrication*




?

***Paradigm shift***

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***Oil Less***

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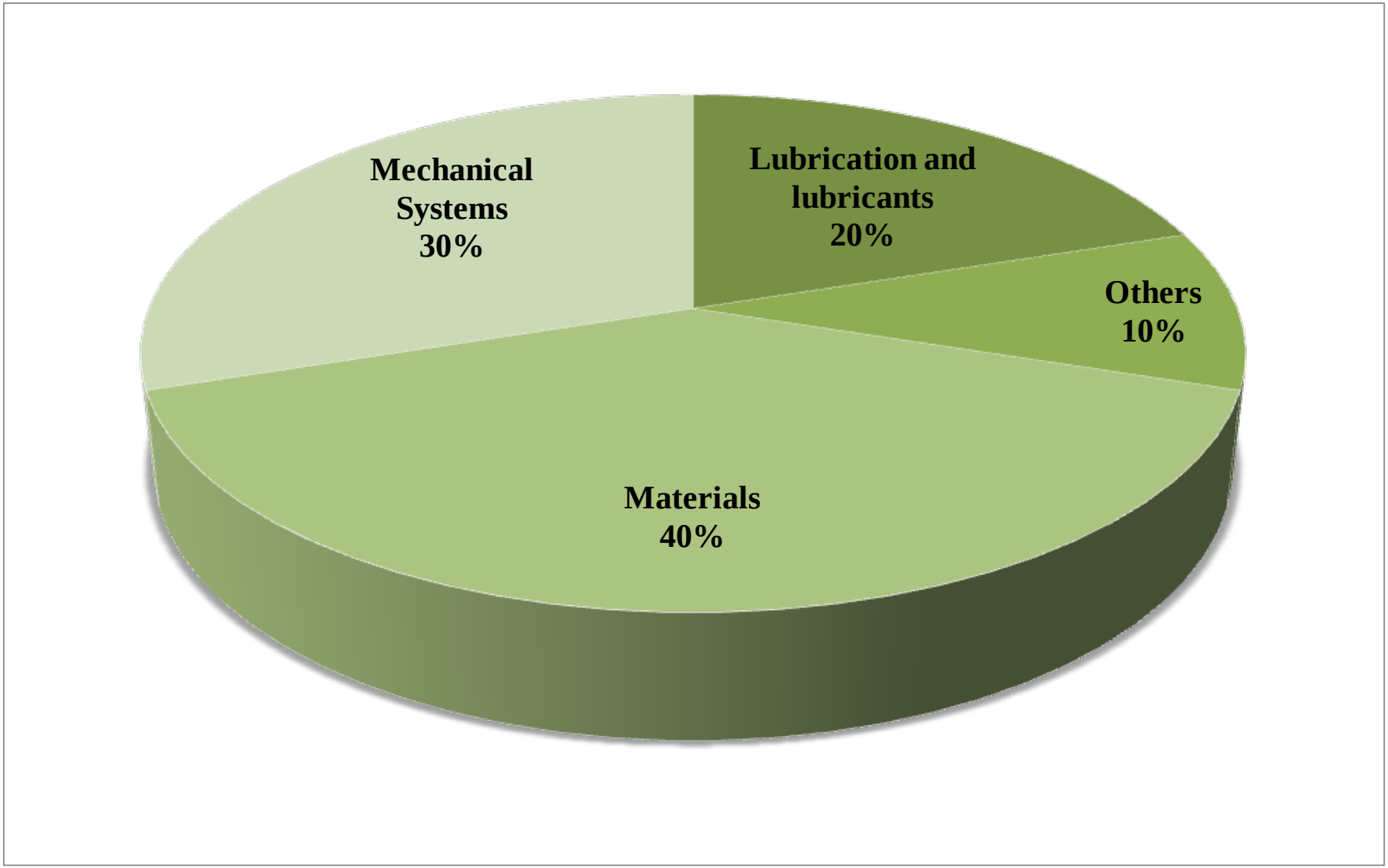
# However ....




*Jost, H.P.; Tribology-Origin and Future; Wear, 136, (1990) 1-17.*

# *WiseMotion®*

## *the world's first oil-free compressor for home appliances*

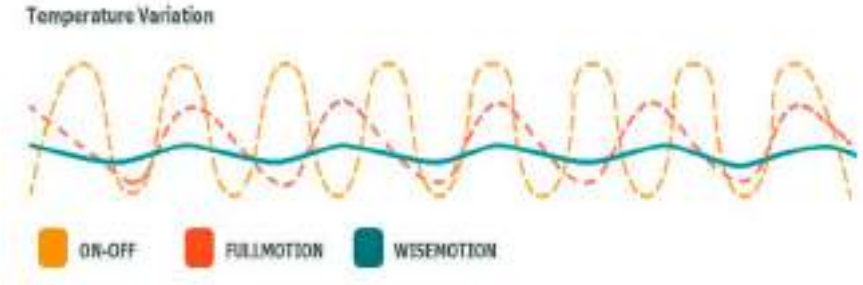
**WISEMOTION®**

- *80+ patents*
- *Linear Motion*
- *Variable displacement*
- *Single tribological contact*
- *NO oil for lubrication*

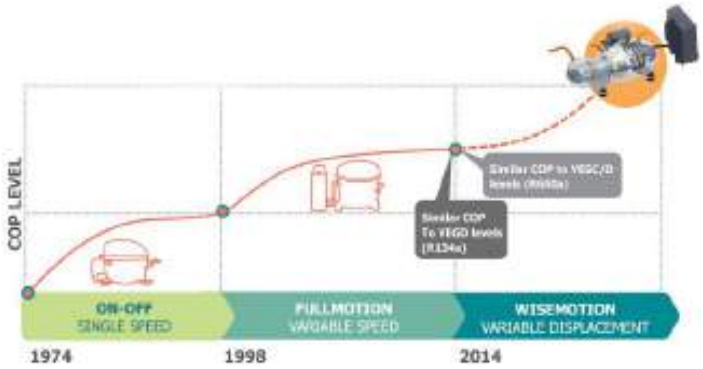
# WISEMOTION®

## *the world's first oil-free compressor for home appliances*


- *free up to 20 liters of cabinet space.*
- *new designs and architectures for refrigerators*




- *less temperature variation*
- *healthier food*.




- *top efficiency compressor*
- *complies with some of today's strictest efficiency regulations*

# *WISEMOTION®*

## *the world's first oil-free compressor for home appliances*

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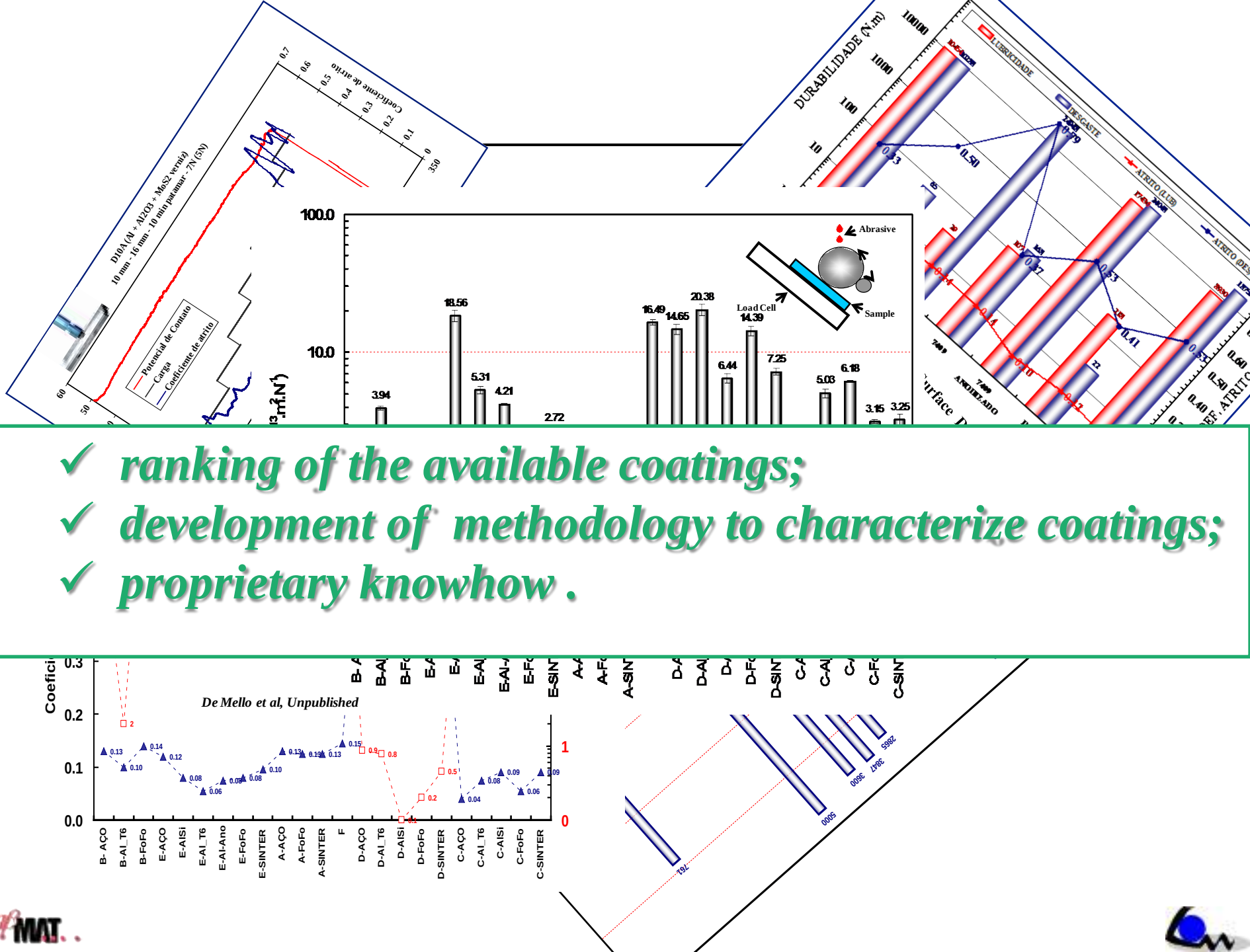
## *Screening commercially available coatings:*

**SUBSTRATE**

- Aluminun
- Anodyzed Al
- Al12%Si
- Al 6351-T6
- Al 6351-T6 Anodized
- 1020 Steel
- Gray cast iron
- Sintered iron

**COATING**

| | Family | Material |
|---|---|---|
| A | DLC | MeC:DLC |
| B | DLC | A:CH |
| C | Layered solid | Me:$MoS_2$ |
| D | Composite (metal) | NiP + PTFE |
| E | Polymer (composite) | PTFE + Polyamide |
| F | Polymer (composite) | Polyamide imide + graphite + PTFE |
| G | Ceramic | Anodyzed Al |
| H | Polymer | PTFE |
| I | DLC | A:CH |
| J | Composite (polymer) | $MoS_2$ Organic Matrix |
| H | Composite (polymer) | $MoS_2$ Inorganic Matrix |




- ✓ *ranking of the available coatings;*
- ✓ *development of methodology to characterize coatings;*
- ✓ *proprietary knowhow .*

*Screening commercially available coatings:*

***In spite of considerable research developments, through more than 2000 published papers from the past 25 years, there exists no single solid lubricant that can provide both low friction and wear over broad use conditions, temperatures and environments.***

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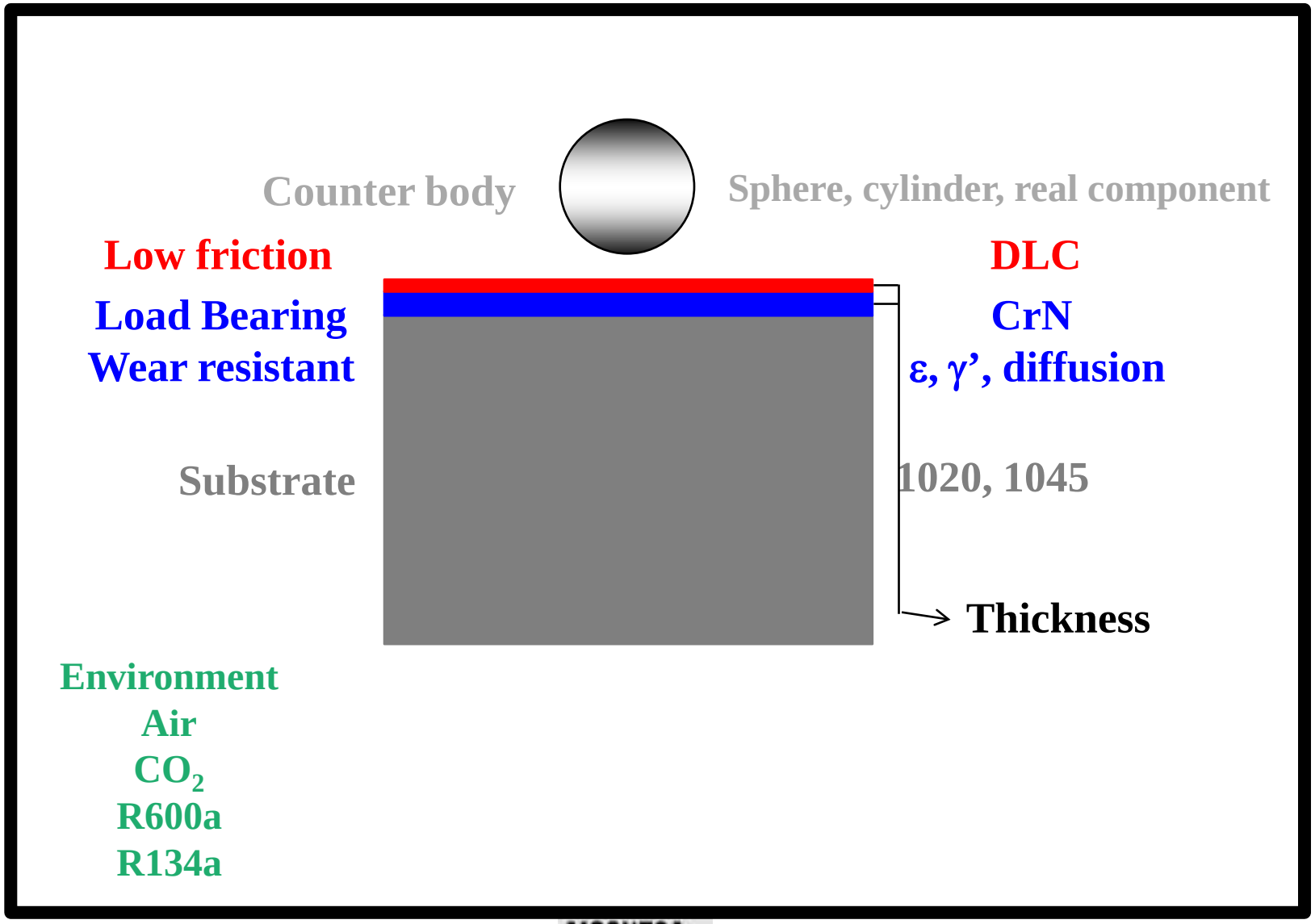
**Multi purpose**

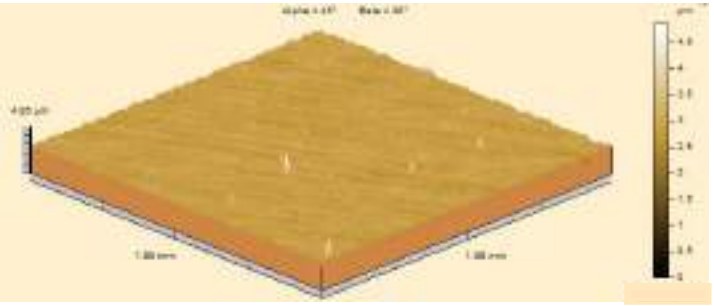
**Multi layer**

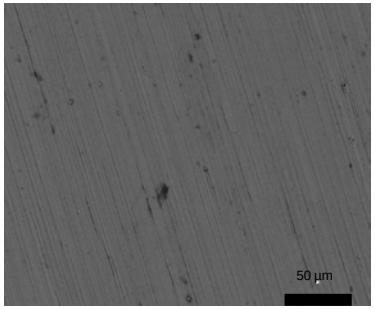
**DLC**

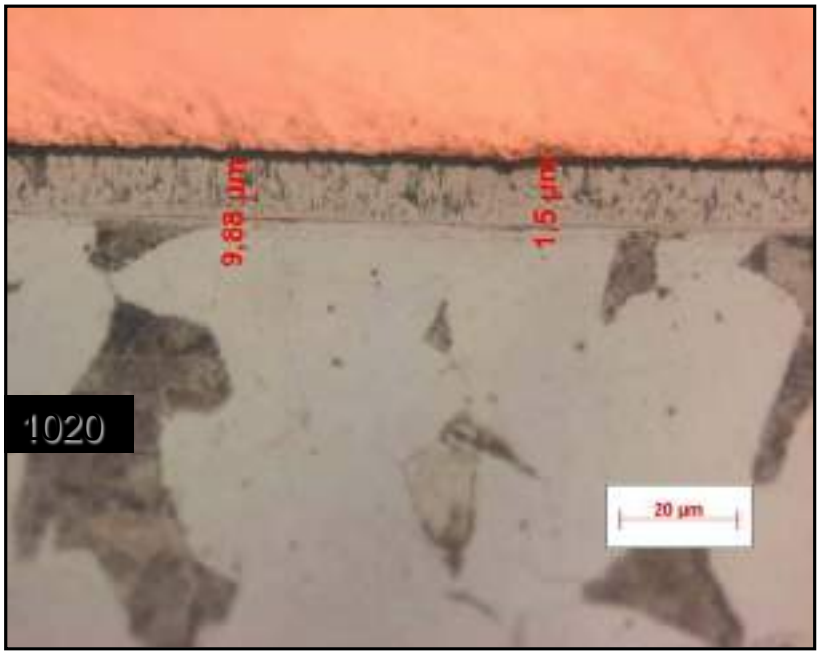
*Donnet, C. and Erdemir, A. , Historical developments and new trends in tribological and solid lubricant coatings, Surface and Coatings Technology 180 – 181 (2004) 76–84*

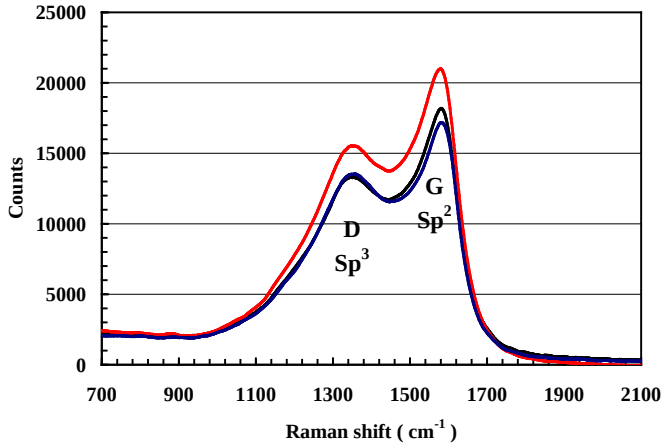

Counter body
Sphere, cylinder, real component
Low friction
DLC
Load Bearing
Wear resistant
CrN
ε, γ', diffusion
Substrate
1020, 1045
Thickness
Environment
Air
$CO_2$
R600a
R134a

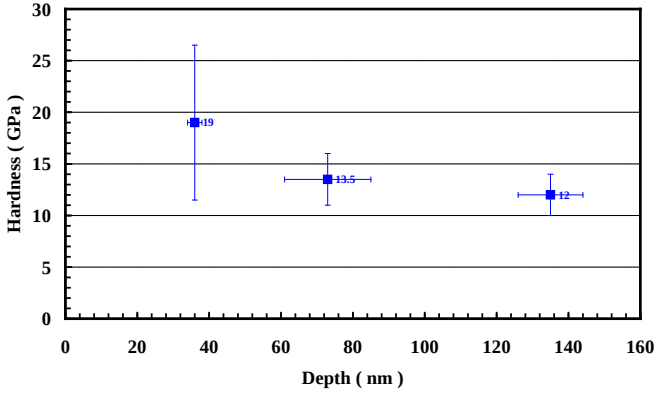
# Effect of the environment:






***Proprietary magnetron sputtered diode multi functional CrN - Si rich DLC on finely ground (Sq= 0.23±0.025 µm) AISI 1020 steel.***

*De Mello, JDB, et al., Wear. v.267, p.907 - 915, 2009*

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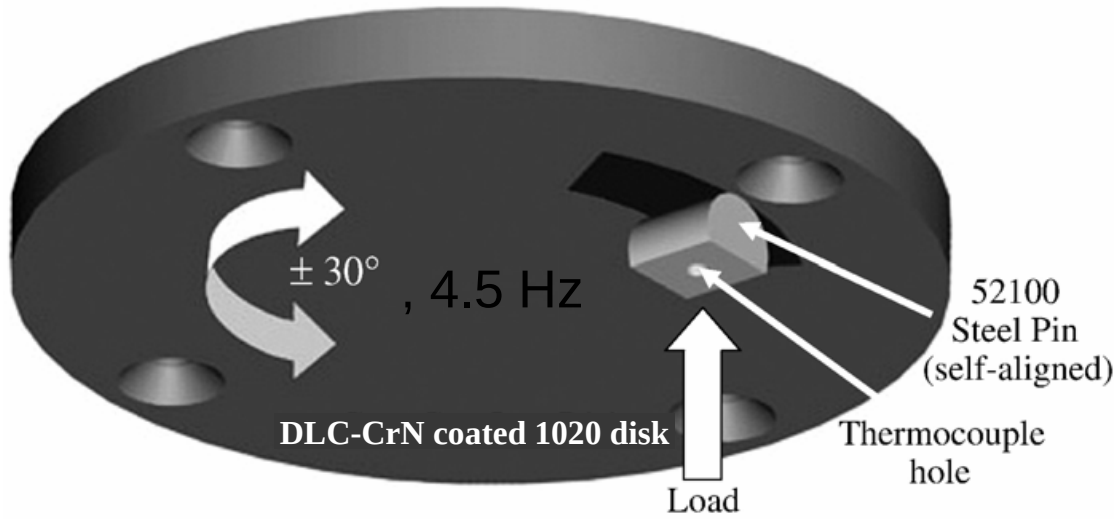
# *Effect of the environment:*

## *High Pressure Tribometer (HTP) - simulating typical operating conditions found in air conditioning and refrigeration compressors.*

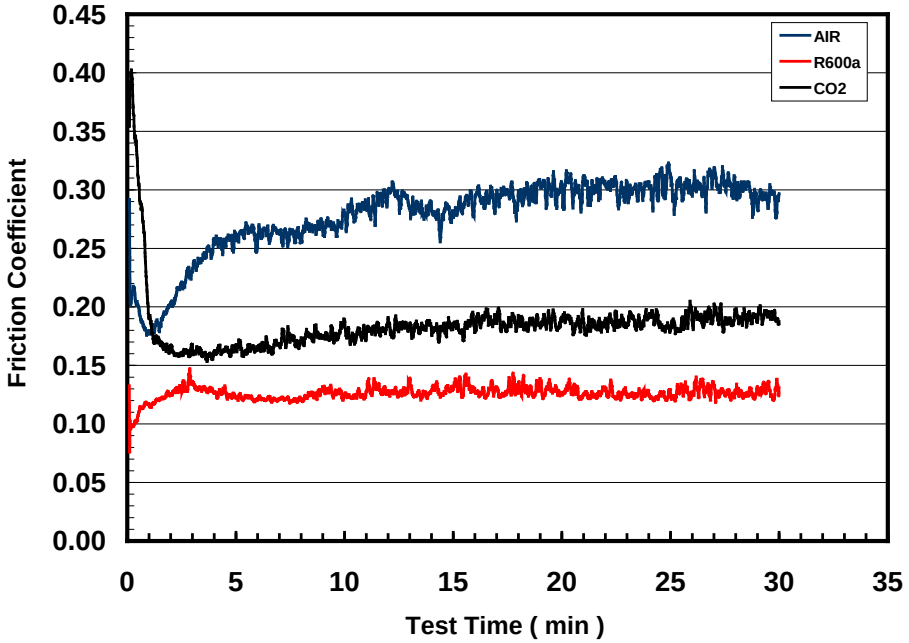
- *Actual environment ( hermetic compressors),*
- *Unlubricated ,*
- *$CO_2$ and R600a at 100 KPa environmental pressure*
- *Reference: unpressurized tests conducted in air.*

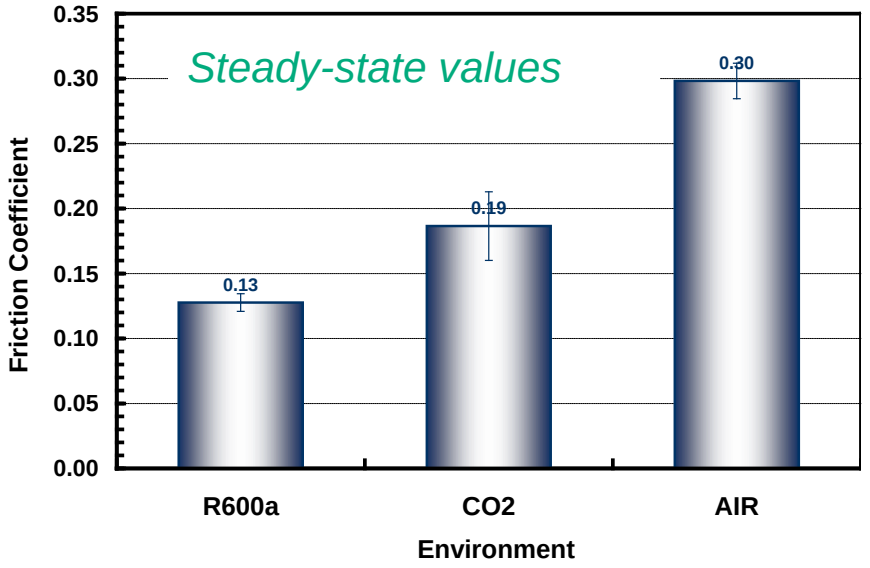


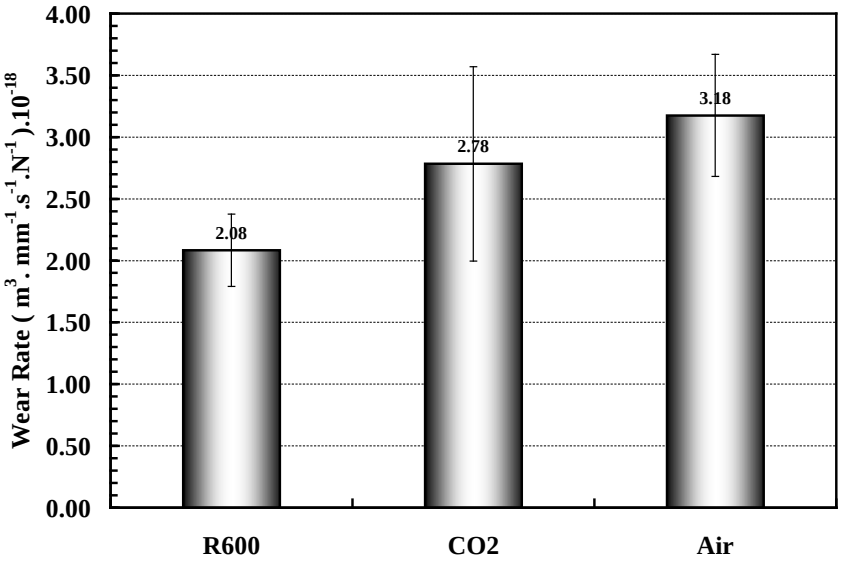


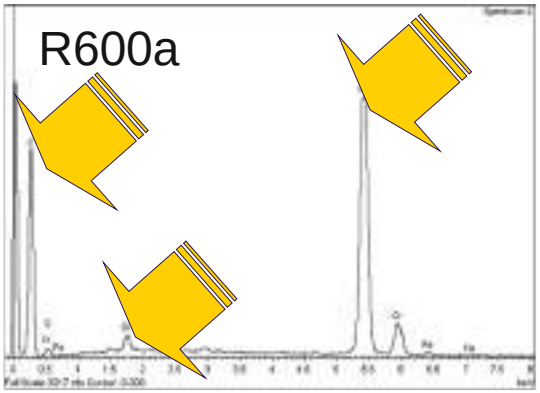
*De Mello, JDB, Binder, R., Demas, N.G., Polycarpou, A.A., Effect of the actual environment present in hermetic compressors on the tribological behaviour of a Si-rich multifunctional DLC coating. Wear. v.267, p.907 - 915, 2009*

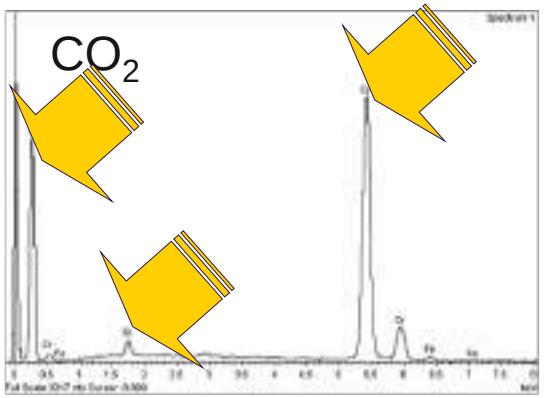
# Effect of the environment:

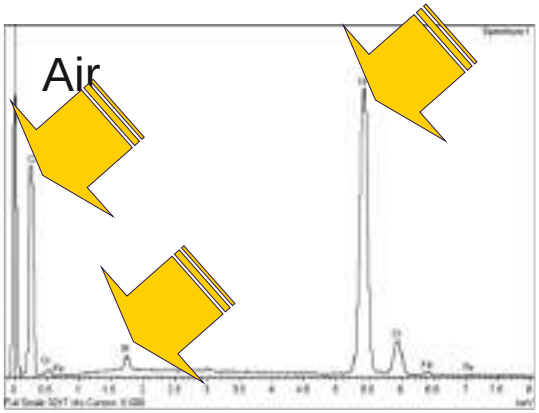


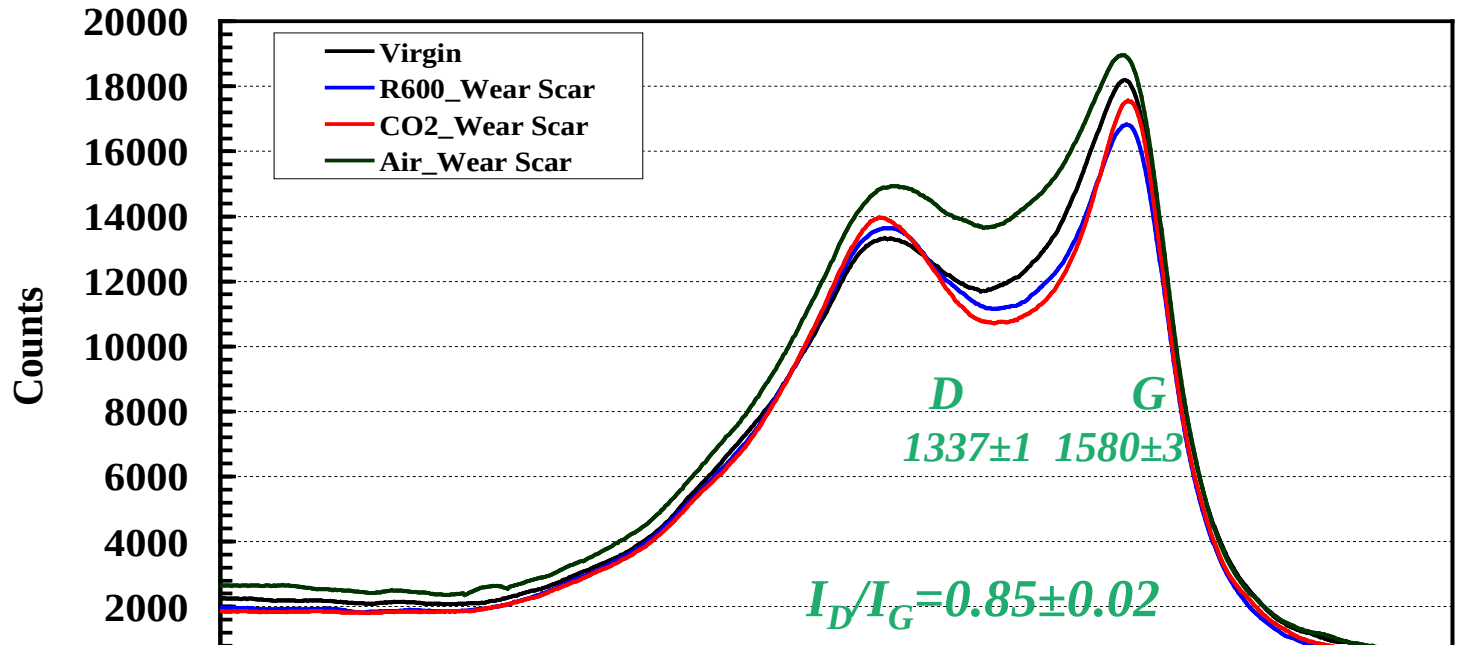





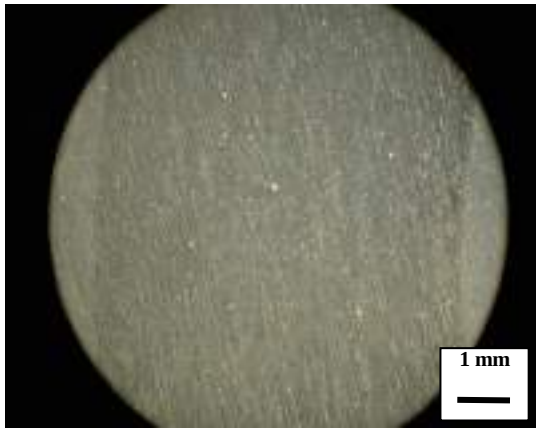



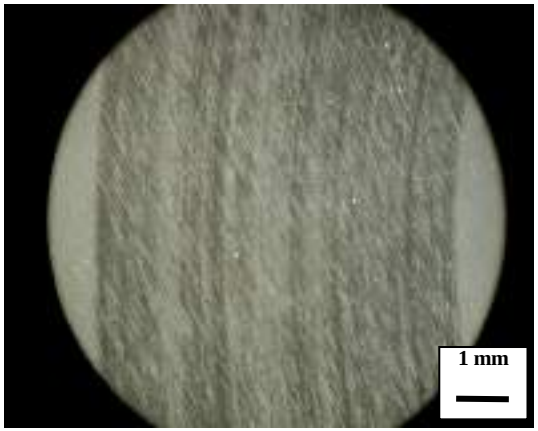




- *Chemically, no remarkable differences between the tribo layers formed in different atmospheres.*

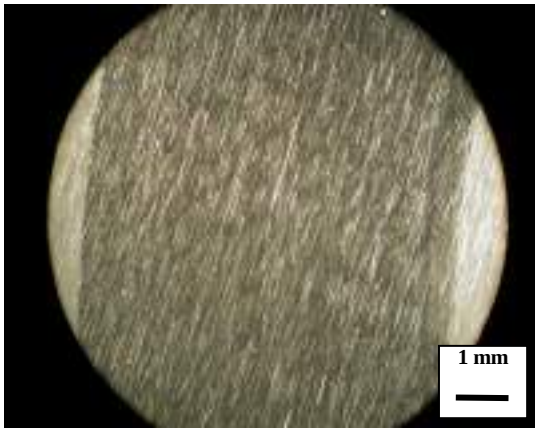
# *Results and discussion:*



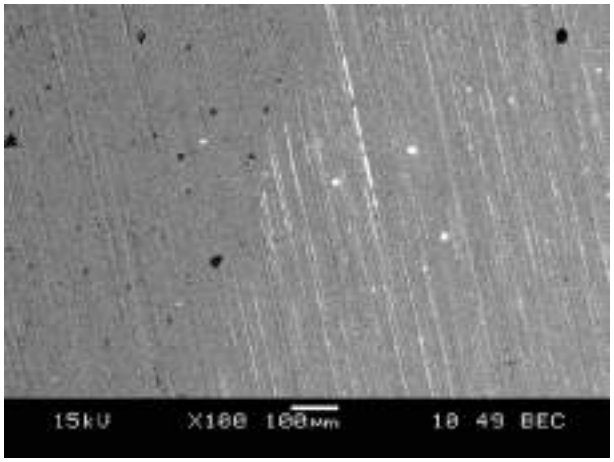

**R600a**

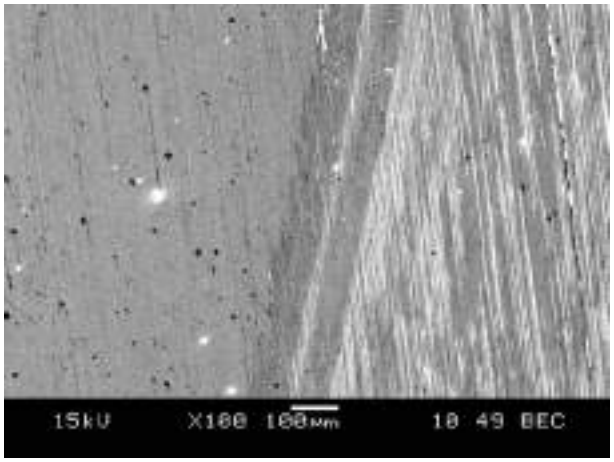


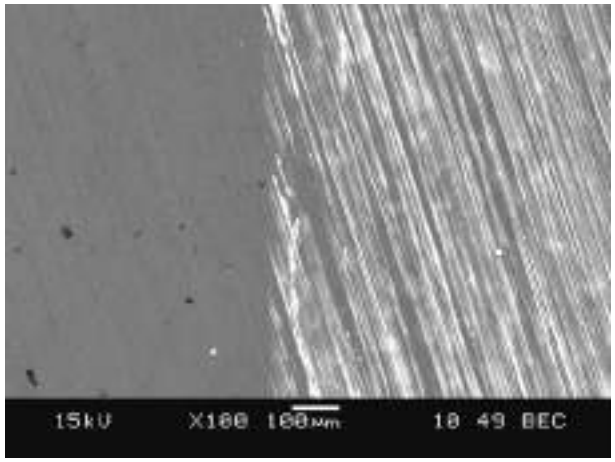

**$CO_2$**




**Air**



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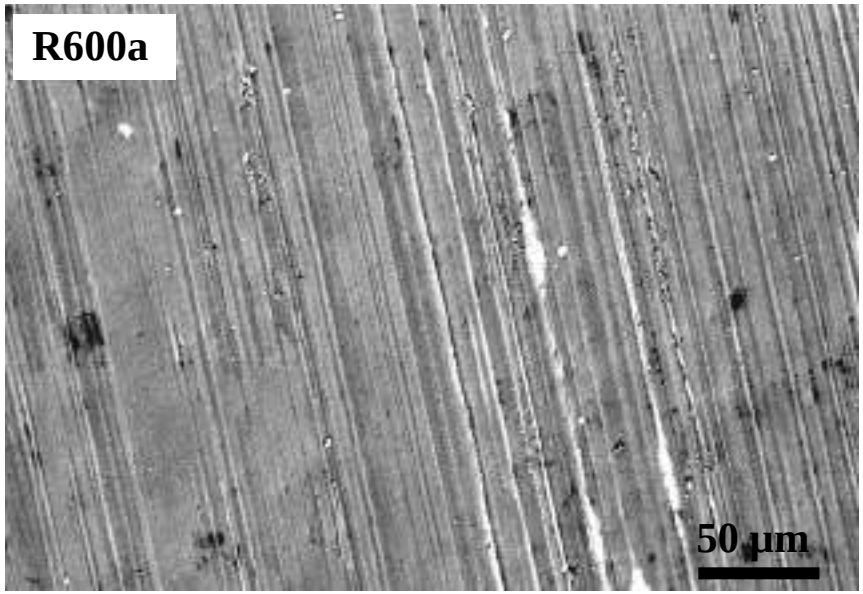


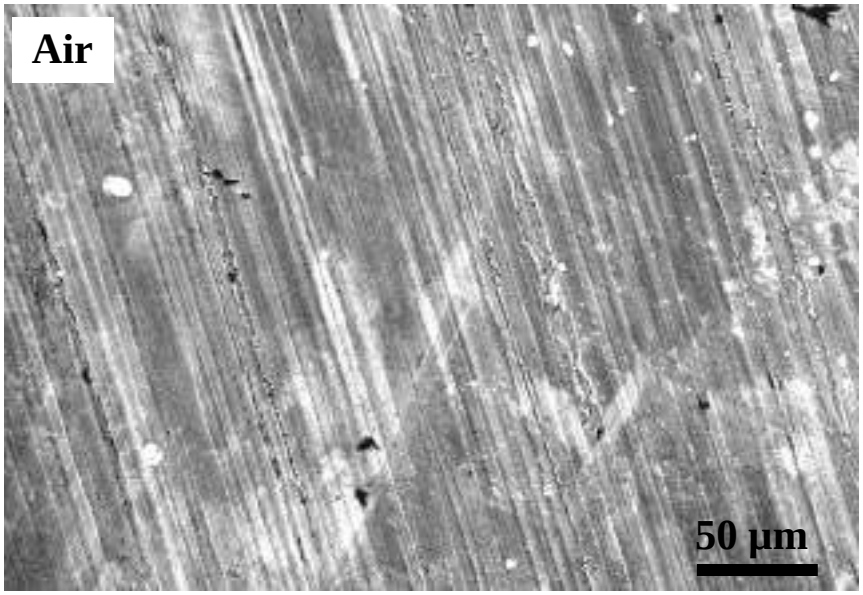

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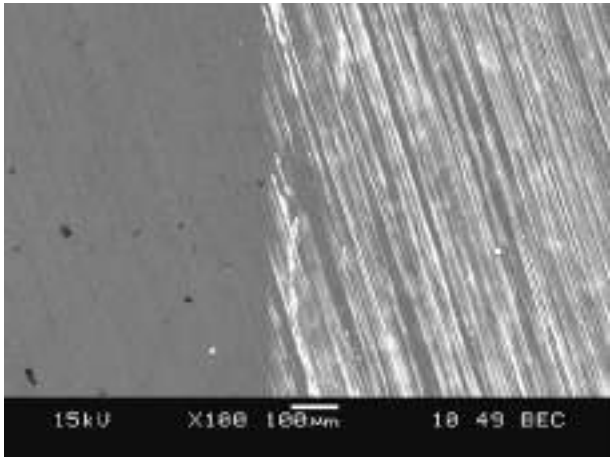
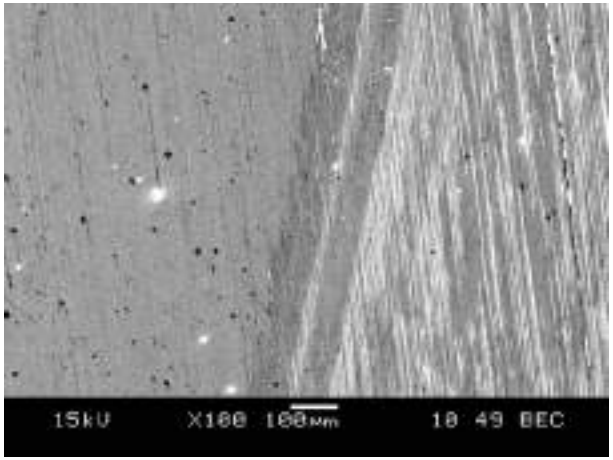
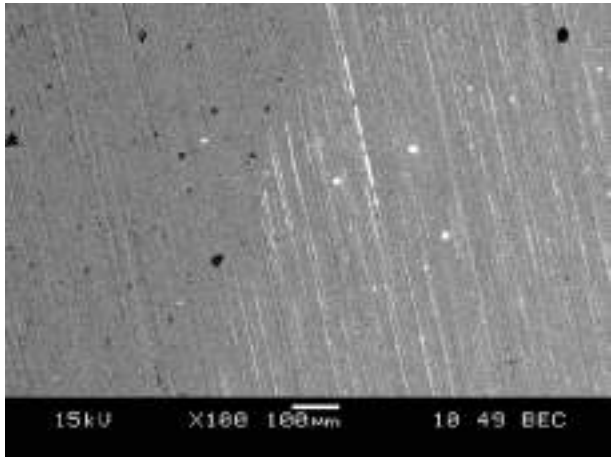
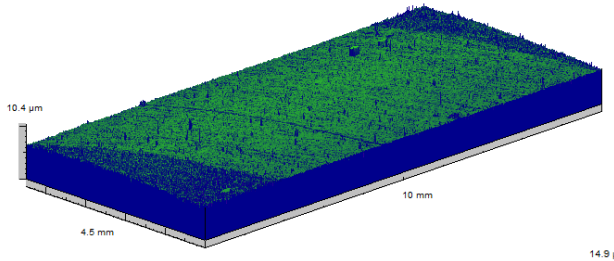


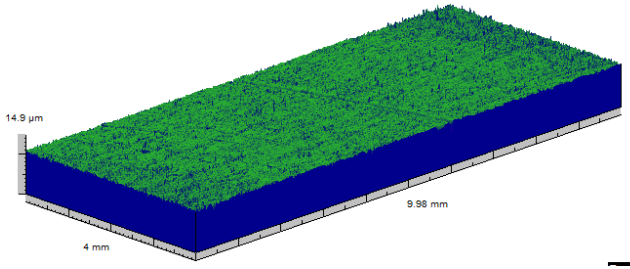



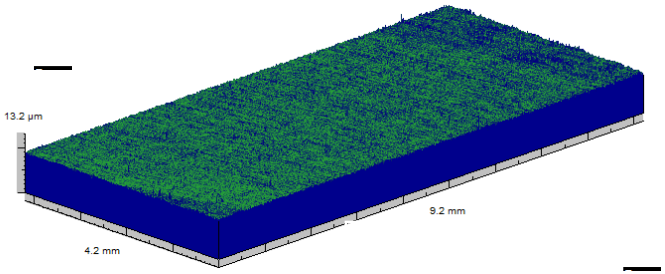

**Air**



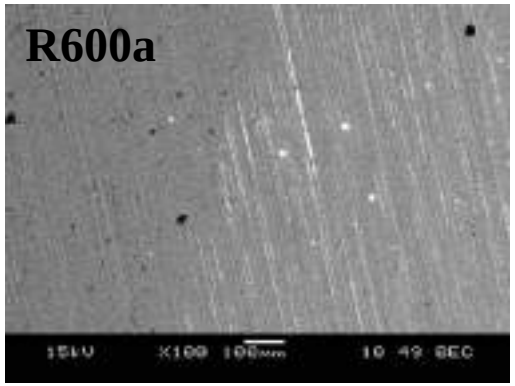

**CO2**

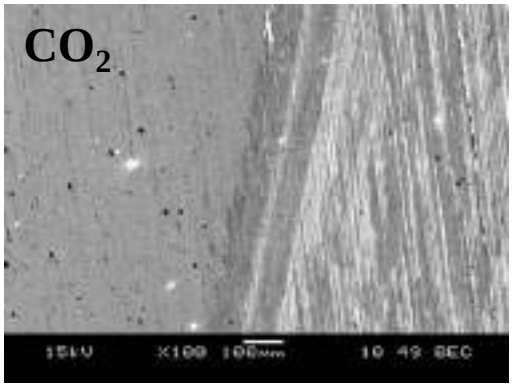


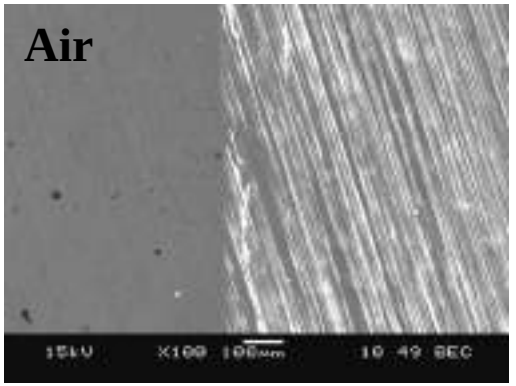

**R600a**

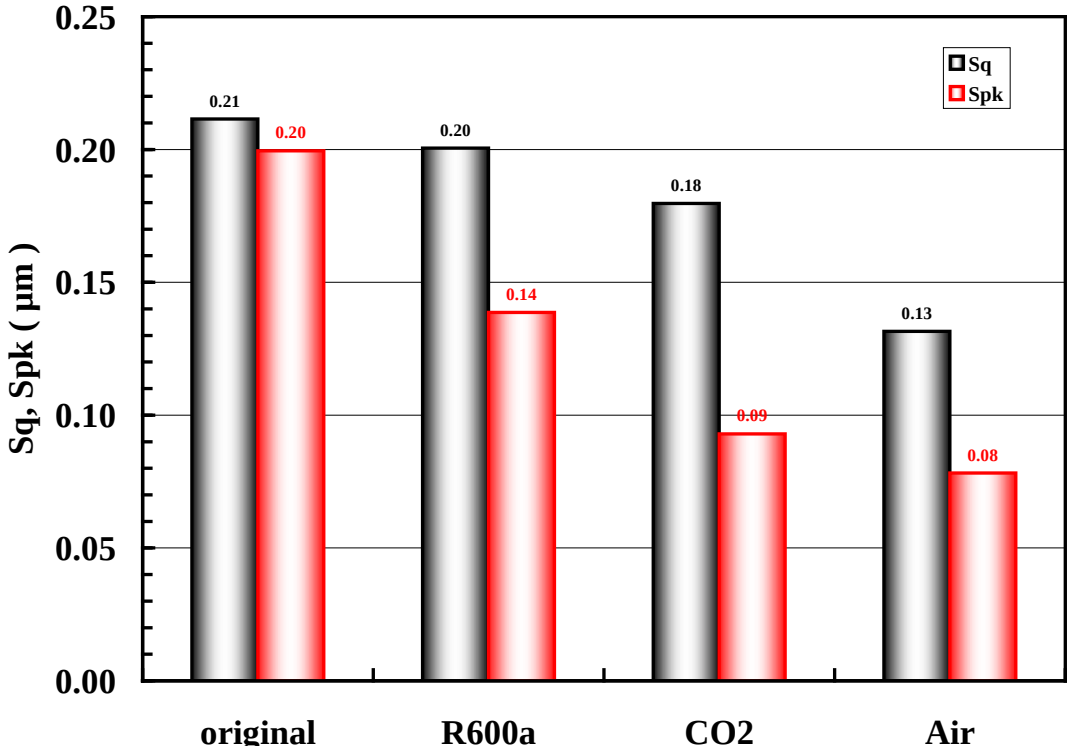


# *Effect of the environment:*



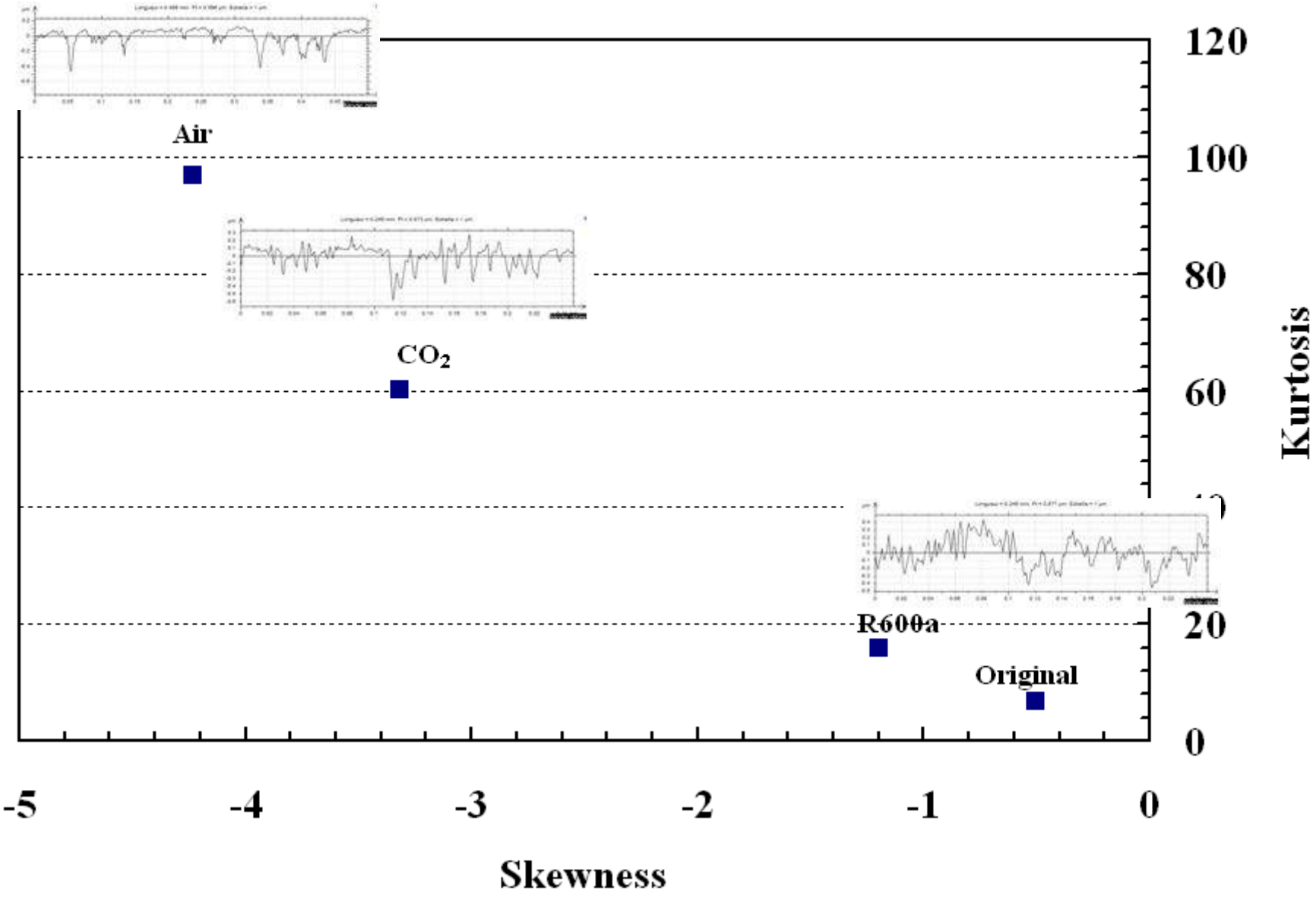




*De Mello, JDB, Binder, R., Demas, N.G., Polycarpou, A.A., Effect of the actual environment present in hermetic compressors on the tribological behaviour of a Si-rich multifunctional DLC coating. Wear. v.267, p.907 - 915, 2009*

# *Results and discussion:*



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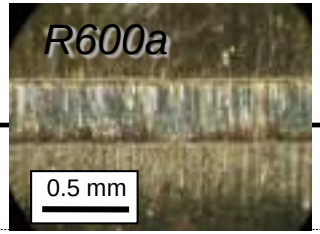
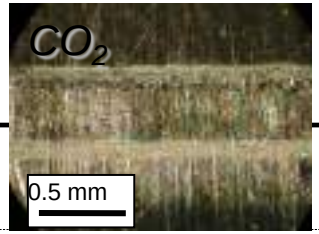
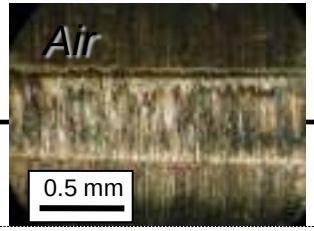


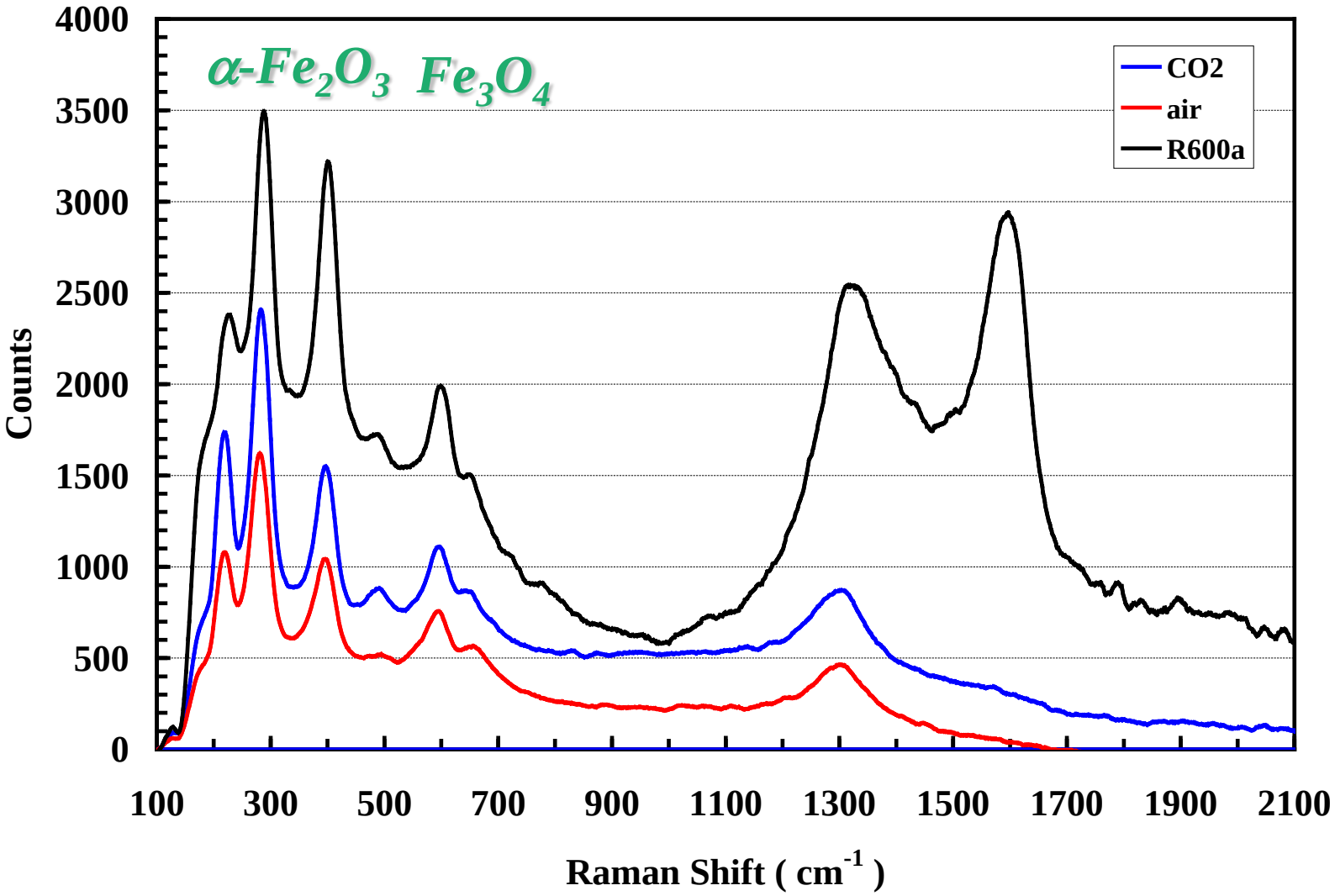







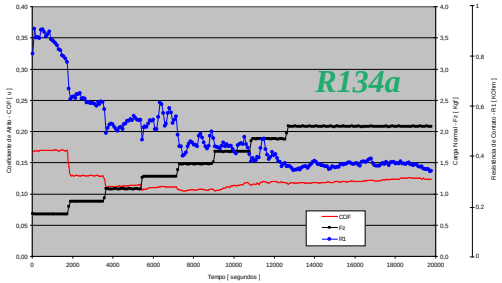
*De Mello, JDB, Binder, R., Demas, N.G., Polycarpou, A.A., Effect of the actual environment present in hermetic compressors on the tribological behaviour of a Si-rich multifunctional DLC coating. Wear. v.267, p.907 - 915, 2009*

# Effect of the environment:

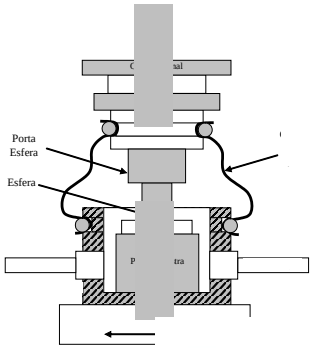


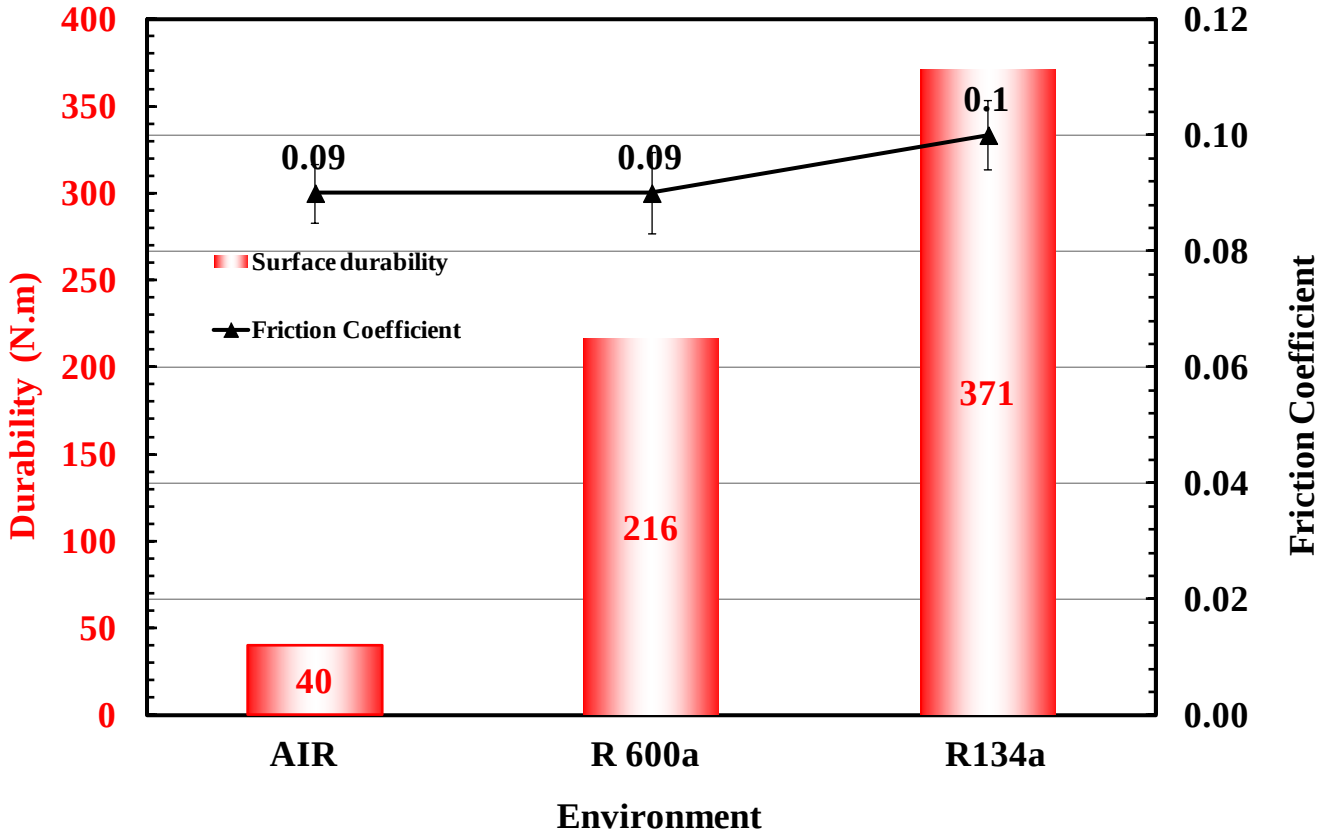

*De Mello, JDB, Binder, R., Demas, N.G., Polycarpou, A.A., Effect of the actual environment present in hermetic compressors on the tribological behaviour of a Si-rich multifunctional DLC coating. Wear. v.267, p.907 - 915, 2009*

# *Effect of the environment:*



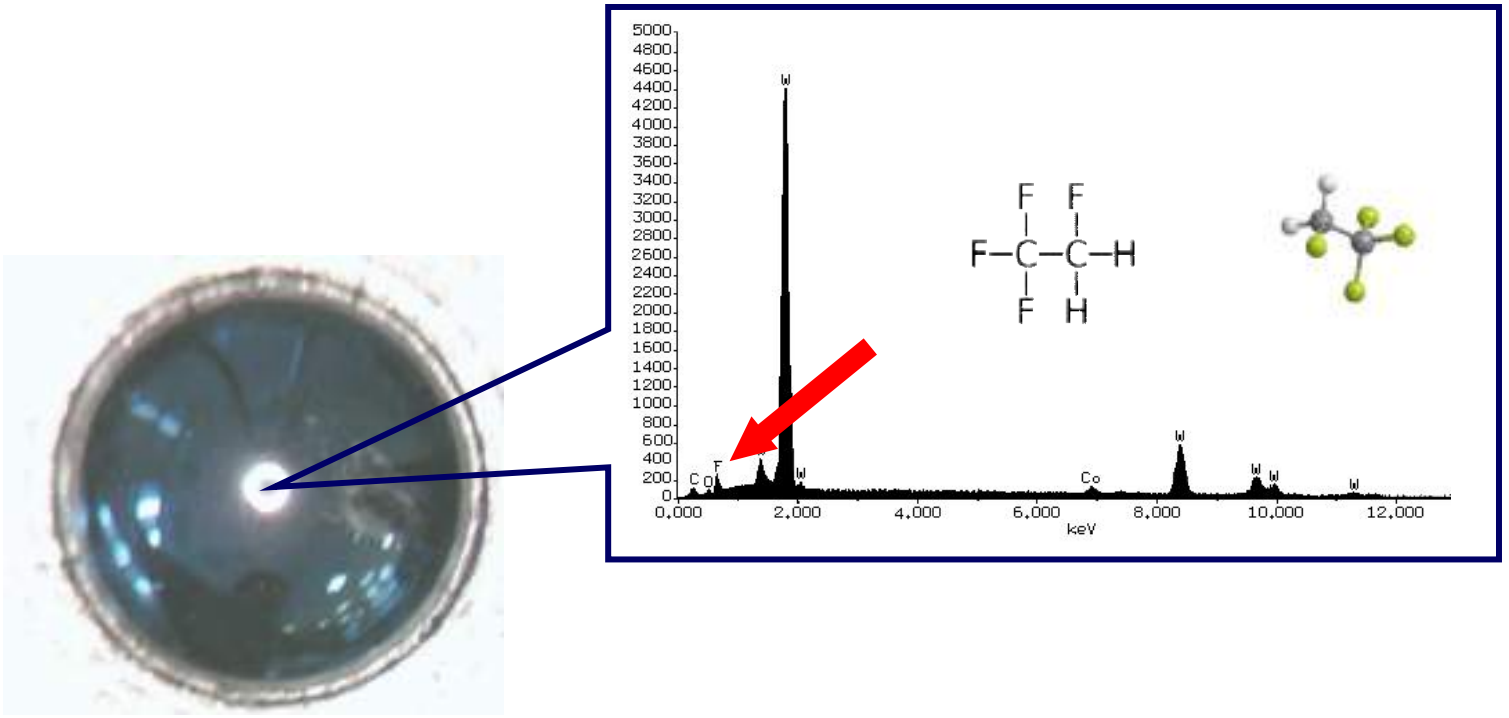




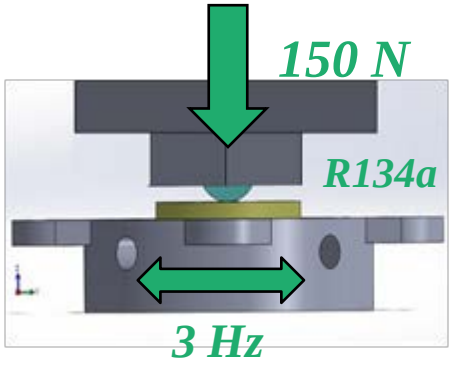

Silverio, M., de Mello, J.D.B., Binder, R., *Effect of refrigerant gases on the tribological behavior of a CrN-SiDLC multifunctional coating applied to soft substrate*. First International Brazilian Conference on Tribology – TriboBr-2010, 2010, Rio de Janeiro – RJ, p.616 - 624

# *Effect of the environment:*



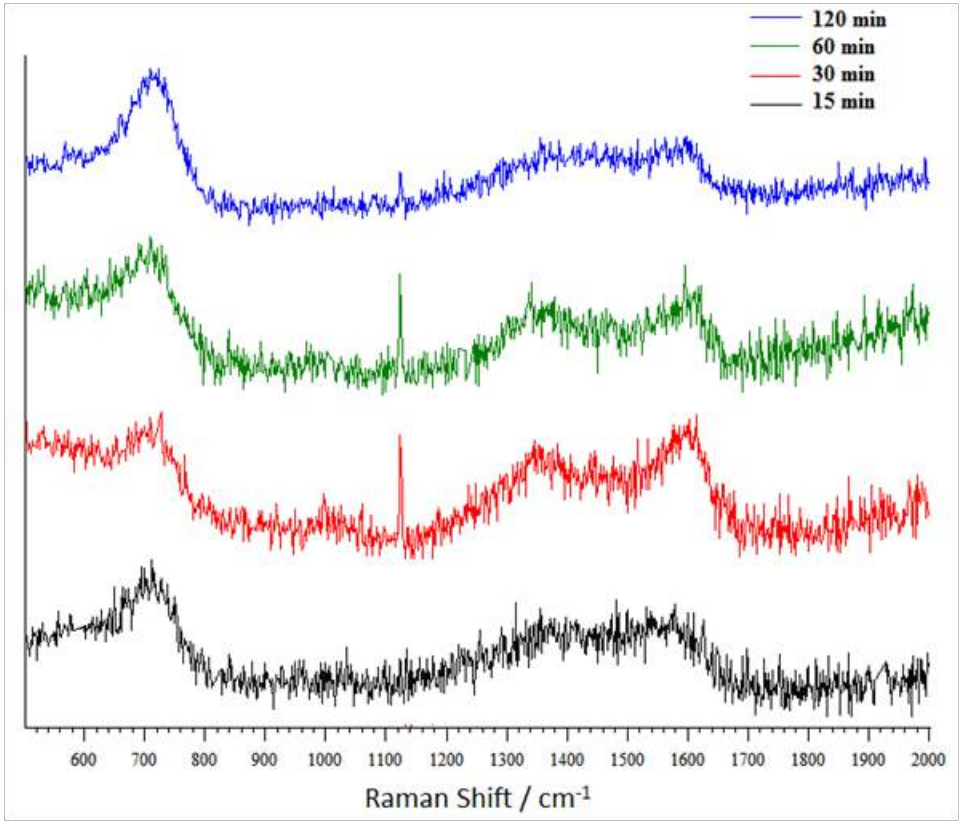

*Silverio, M., de Mello, J.D.B., Binder, R., Effect of refrigerant gases on the tribological behavior of a CrN-SiDLC multifunctional coating applied to soft substrate. First International Brazilian Conference on Tribology – TriboBr-2010, 2010, Rio de Janeiro – RJ, p.616 - 624*

# Effect of the environment:



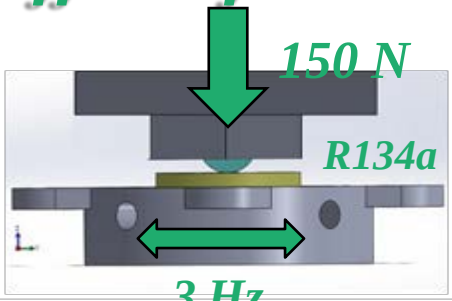

DLC

AISI 304

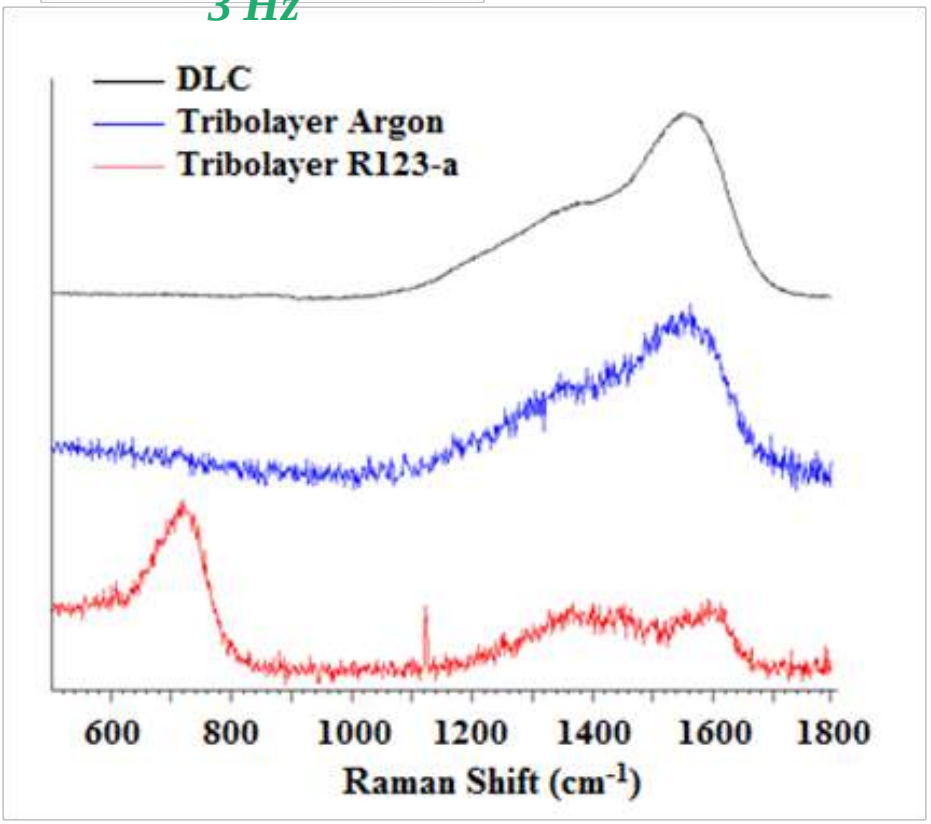



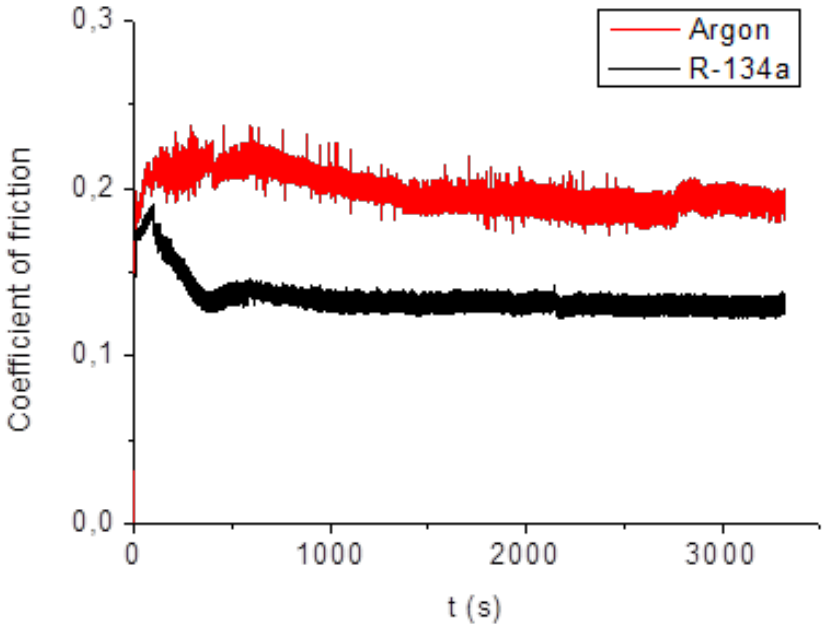

*Barbosa, M.V.; Hammes, G.; Binder, C.; Klein, A. N.; De Mello J. D. B.; Physicochemical characterization of tribolayers by Micro-Raman and GDOES analyses , Tribology International, v 81, p223-230, 2015.*

# Effect of the environment:








*Barbosa, M.V.; Hammes, G.; Binder, C.; Klein, A. N.; De Mello J. D. B.; Physicochemical characterization of tribolayers by Micro-Raman and GDOES analyses , Tribology International, v 81, p223-230, 2015.*

# *Effect of layers thickness:*

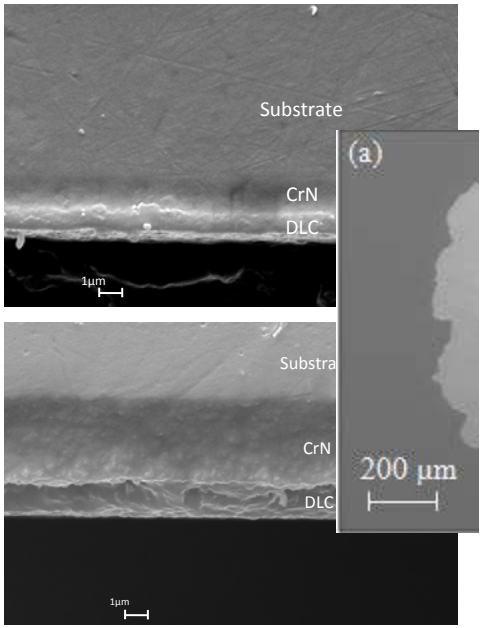
## *Proprietary magnetron sputtered diode multi functional CrN - Si rich DLC on finely ground (Sq= 0.23±0.025 µm) AISI 1020 steel.*

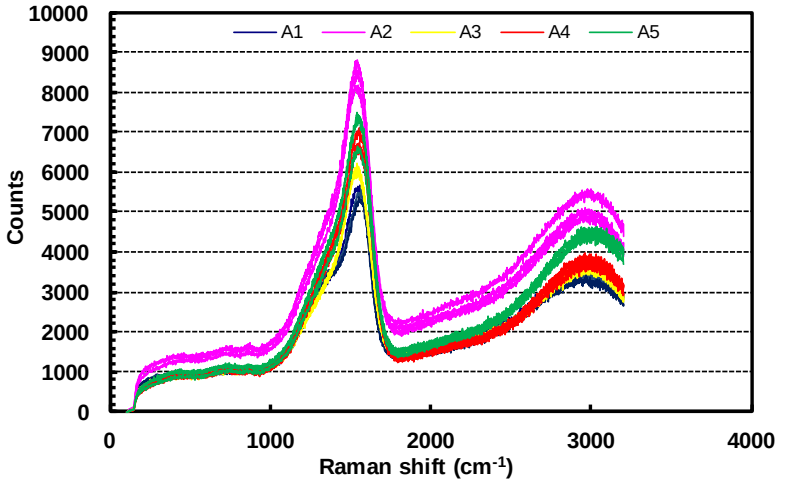
| Sample | | DLC | | CrN | |
|---|---|---|---|---|---|
| | | Thickness (µm) | E (GPa) | Thickness (µm) | E (GPa) |
| Family 1 | 1_A | 1.36±0.05 | 111 | 2.72±0.07 | 86 |
| | 1_B | 1.78±0.07 | 105 | 3.19±0.05 | 84 |
| | 1_C | 1.53±0.05 | 81 | 3.49±0.09 | 75 |
| Family 2 | 2_A | 1.14±0.06 | 220 | 1.44±0.08 | 307 |
| | 2_B | 1.23±0.05 | 203 | 1.38±0.05 | 235 |

*Thin*

*2 families*

*Thick*



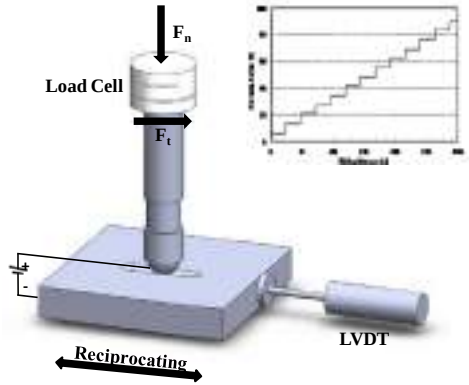



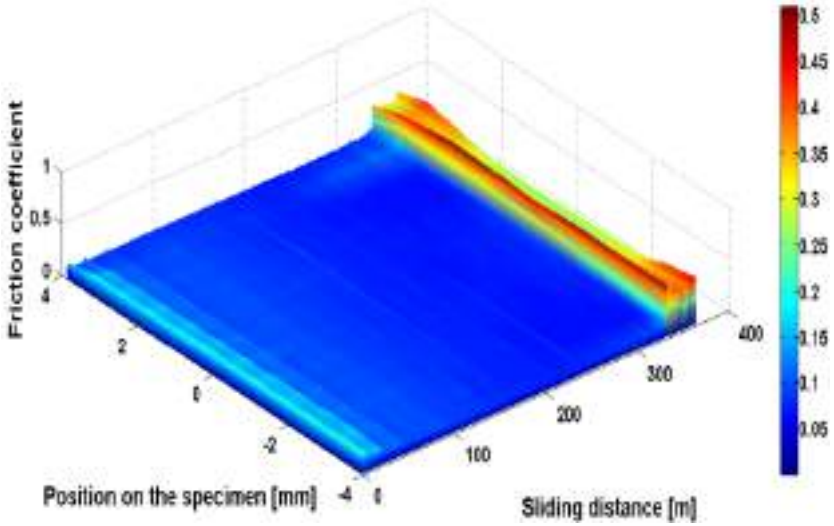

*L.O.C. Lara, J.D.B. De Mello, Influence of layer thickness on hardness and scratch resistance of Si-DLC/CrN coatings, Tribology - Materials, Surfaces & Interfaces v.6, p 168, 2012 .*

# *Effect of layers thickness:*

- **Modified *PLINT & PARTNERS TE 67 - High frequency acquisition system; LVDT; LabVIEW® - Matlab ®***

## *3D Triboscopy*



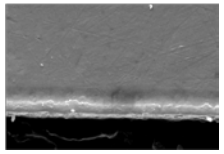



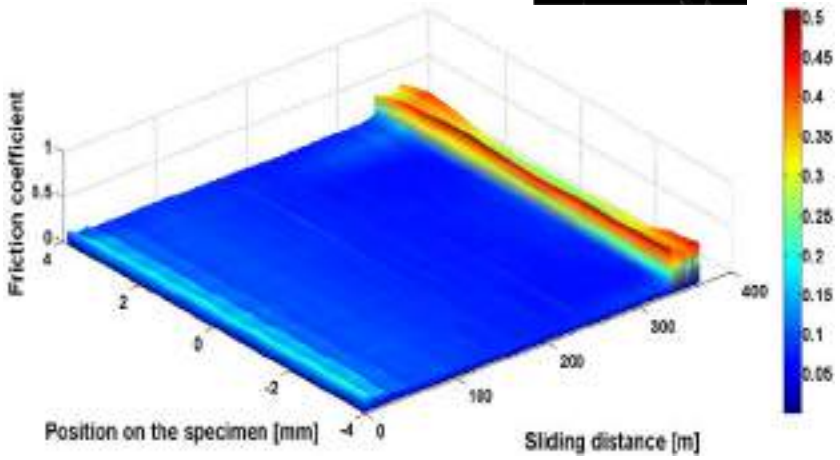

- *2D proposed by Belin-1993;*
- *Locate microscopic tribological events and study their evolution during the test;*
- *Information with local details as well as a global evolution of the tribological phenomena.*
- *High spatial and temporal resolution;*
- *3D triboscopic map where z is the variable being measured (friction coefficient), x is the position of the counter body within each cycle (measured by an additional LVDT sensor) of test and y is the total sliding distance*

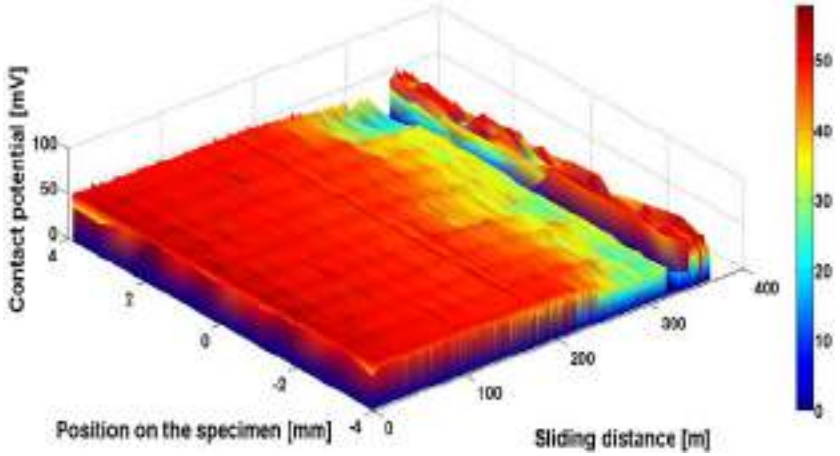
*M. B. dos Santos, H.L. Costa, J.D.B. de Mello, Potentiality of 3D triboscopy to monitor friction and wear, Wear (2014), p.1134 - 1144.*

# *Effect of layers thickness:*

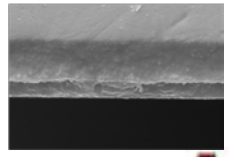
## *Thin*

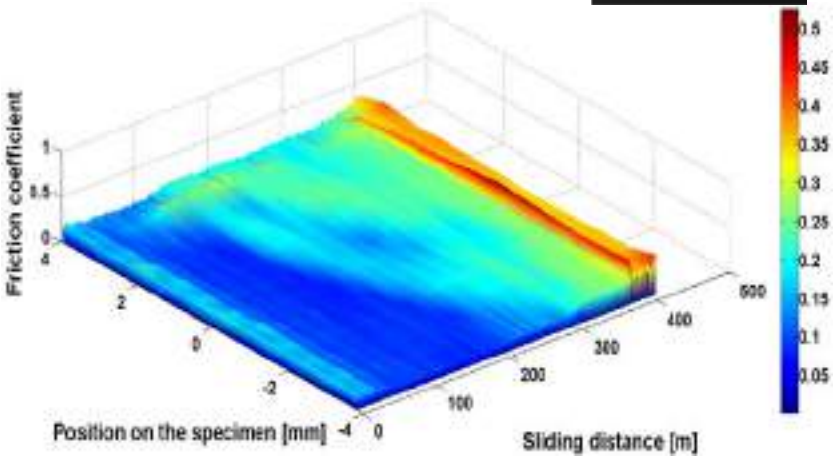


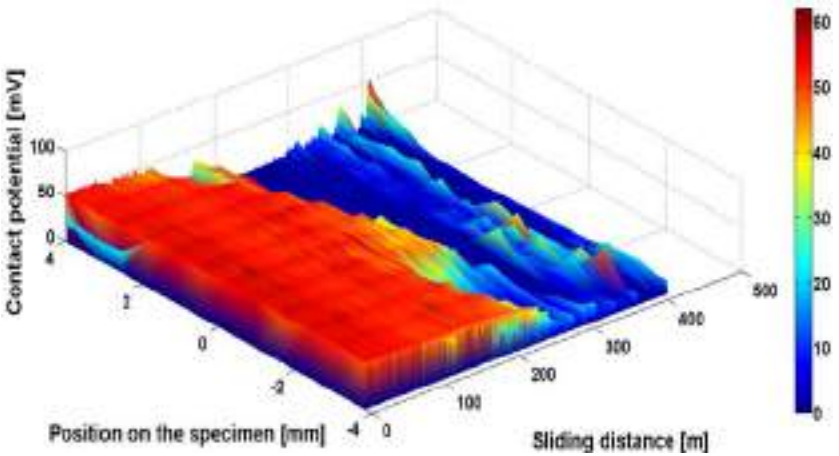



## *Thick*

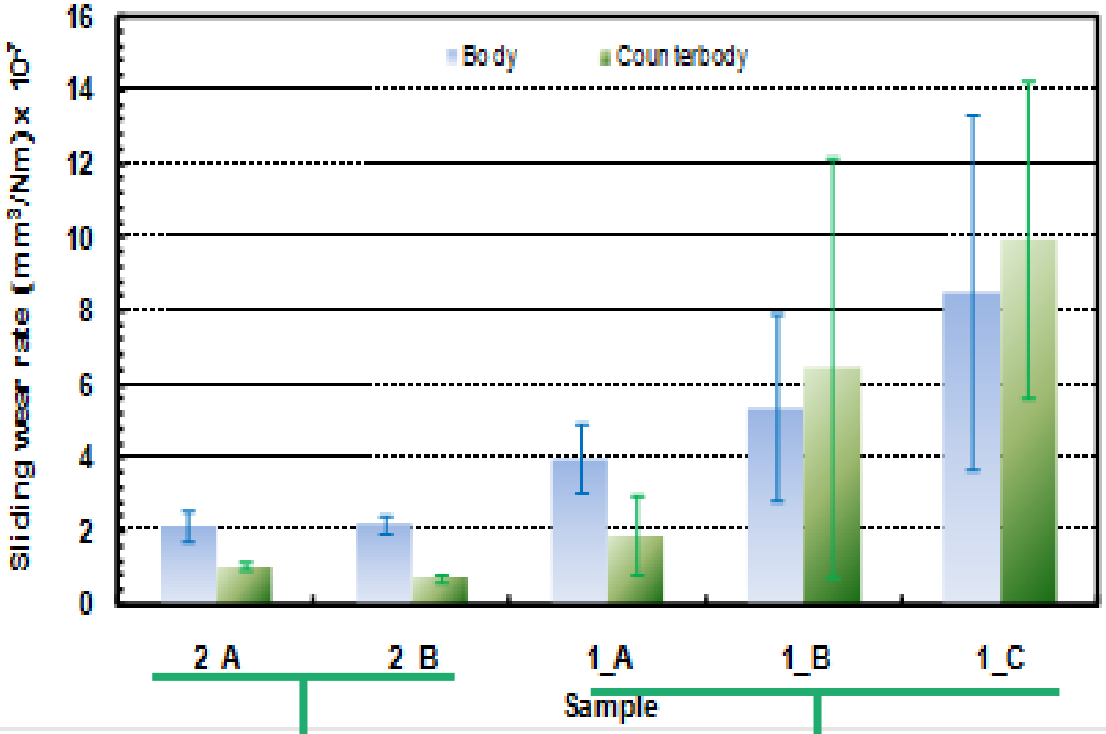


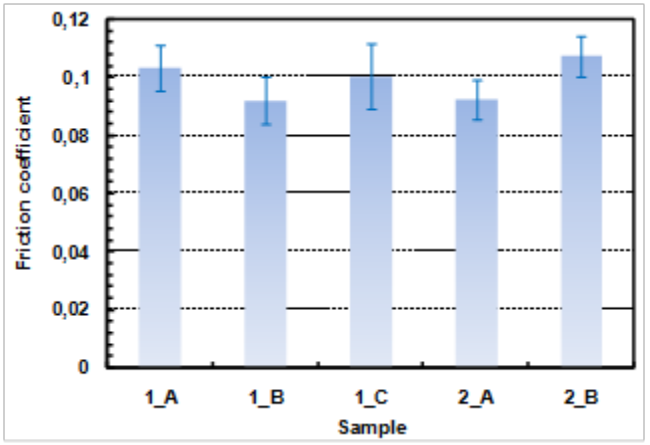


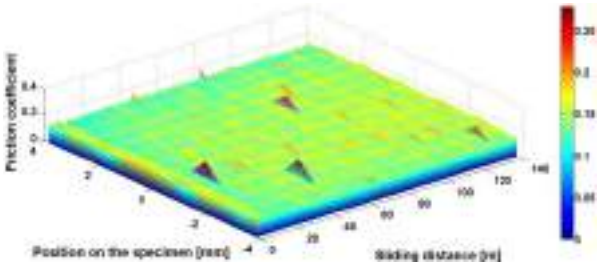



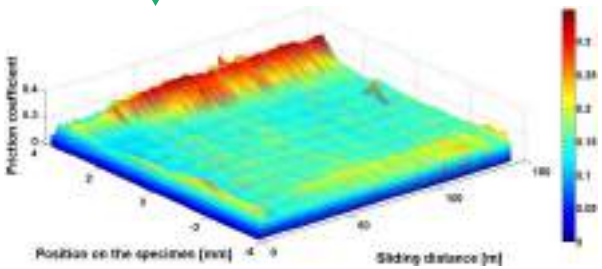

*L. O. C. Lara, H. L. Costa, J. D. B. De Mello, Influence of Layer Thickness on Sliding Wear of Multifunctional Tribological Coatings, Industrial Lubrication and Tribology, (2015), v.460, p.460 - 467,*

# Effect of layers thickness: Constant normal load



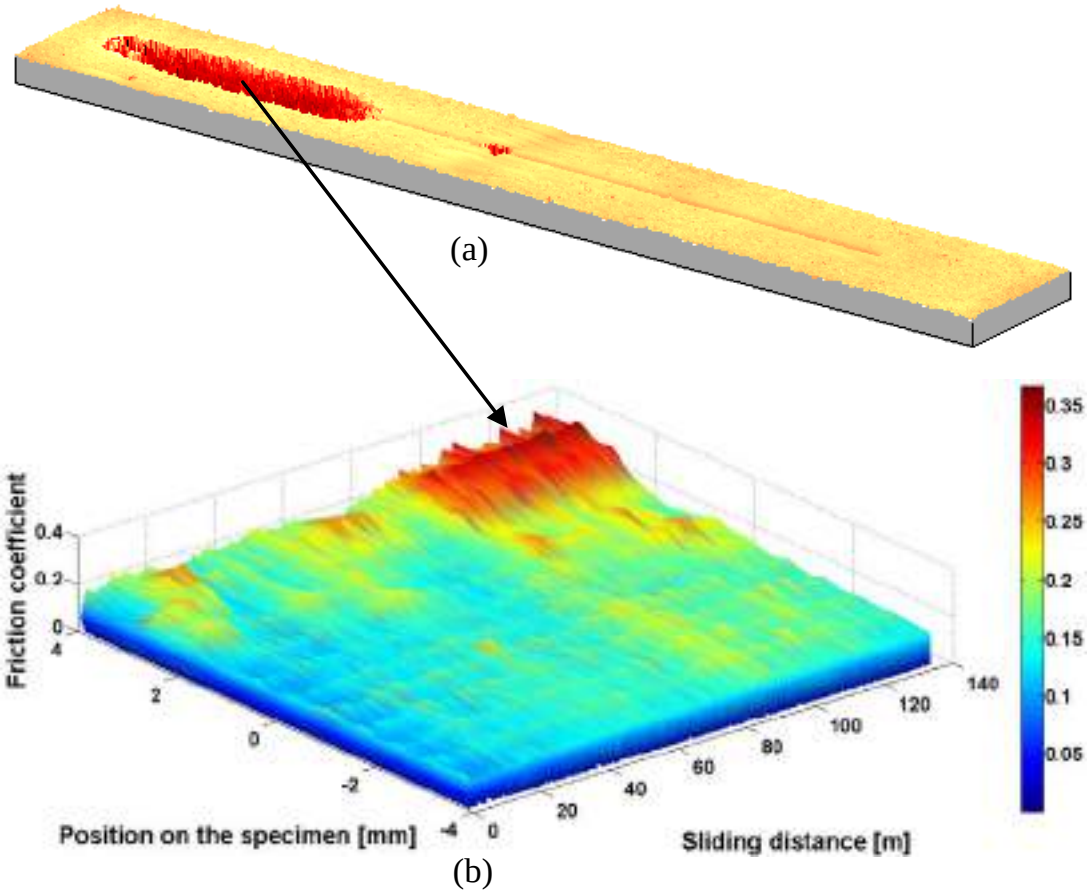



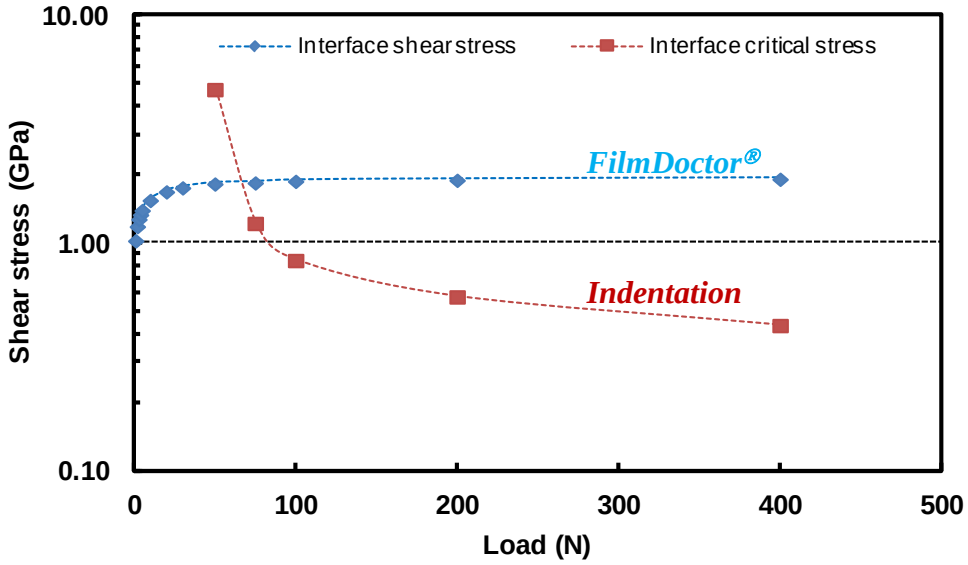

*L. O. C. Lara, H. L. Costa, J. D. B. De Mello, Influence of Layer Thickness on Sliding Wear of Multifunctional Tribological Coatings, Industrial Lubrication and Tribology, (2015), v.460, p.460 - 467,*

# Effect of layers thickness: Constant normal load

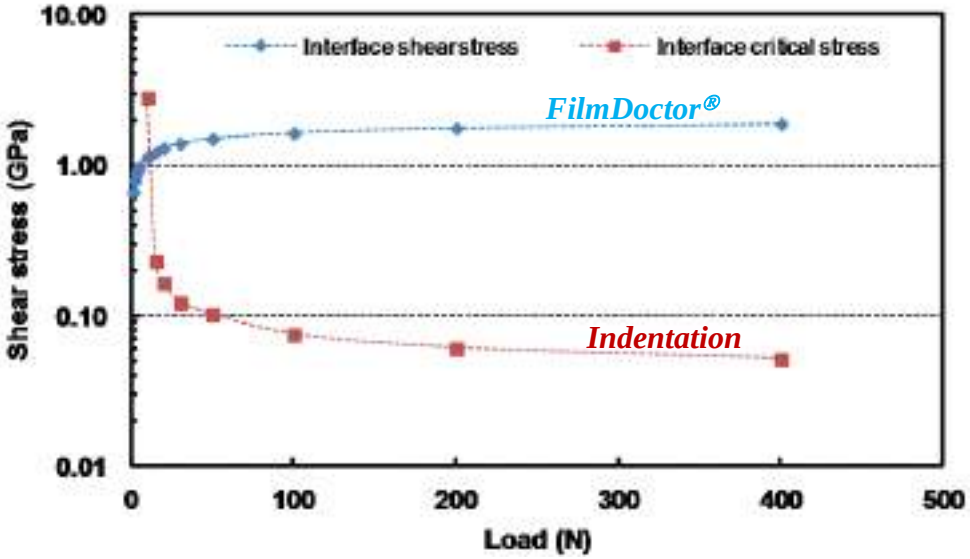



*L. O. C. Lara, H. L. Costa, J. D. B. De Mello, Influence of Layer Thickness on Sliding Wear of Multifunctional Tribological Coatings, Industrial Lubrication and Tribology, (2015), v.460, p.460 - 467,*

# Effect of layers thickness:




**Thin = 50 – 100 N**

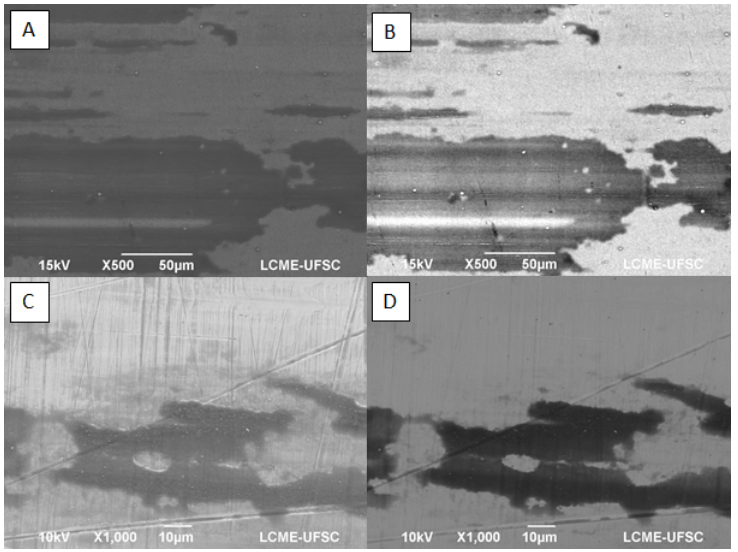



**Thick = 10 N**

*L. O. C. Lara,, J. D. B. De Mello, Quantitative measurement of the interface adhesion of a multifunctional coating, Nanobioletters, (2015), in press*

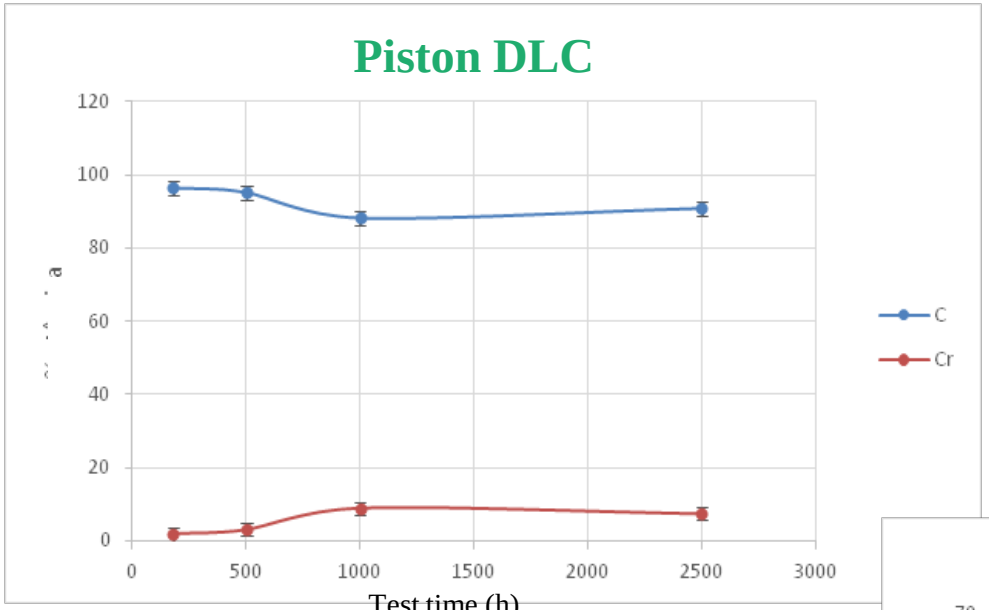
# Evolution and stability of tribolayers:

- Home made emulator
- Testing the real components
- Special atmosphere
- 350 Hz
- Test time: 180, 500, 1000 and 2500 h

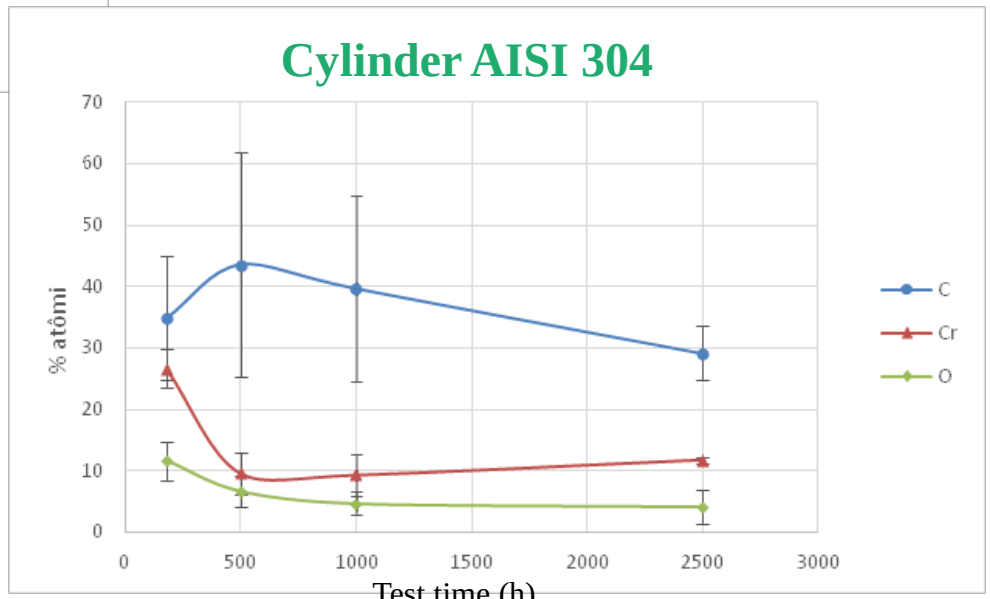



*Salvaro, D et al , Genesis and stability of tribolayers in solid lubrication: case of pair DLC-STAINLESS steel, Proceedings of TriboBR2014- Second International Brazilian Conference on Tribology, November 2014, Brazil also Journal of Materials Research Technology, (2015), In press.*

# Evolution and stability of tribolayers:

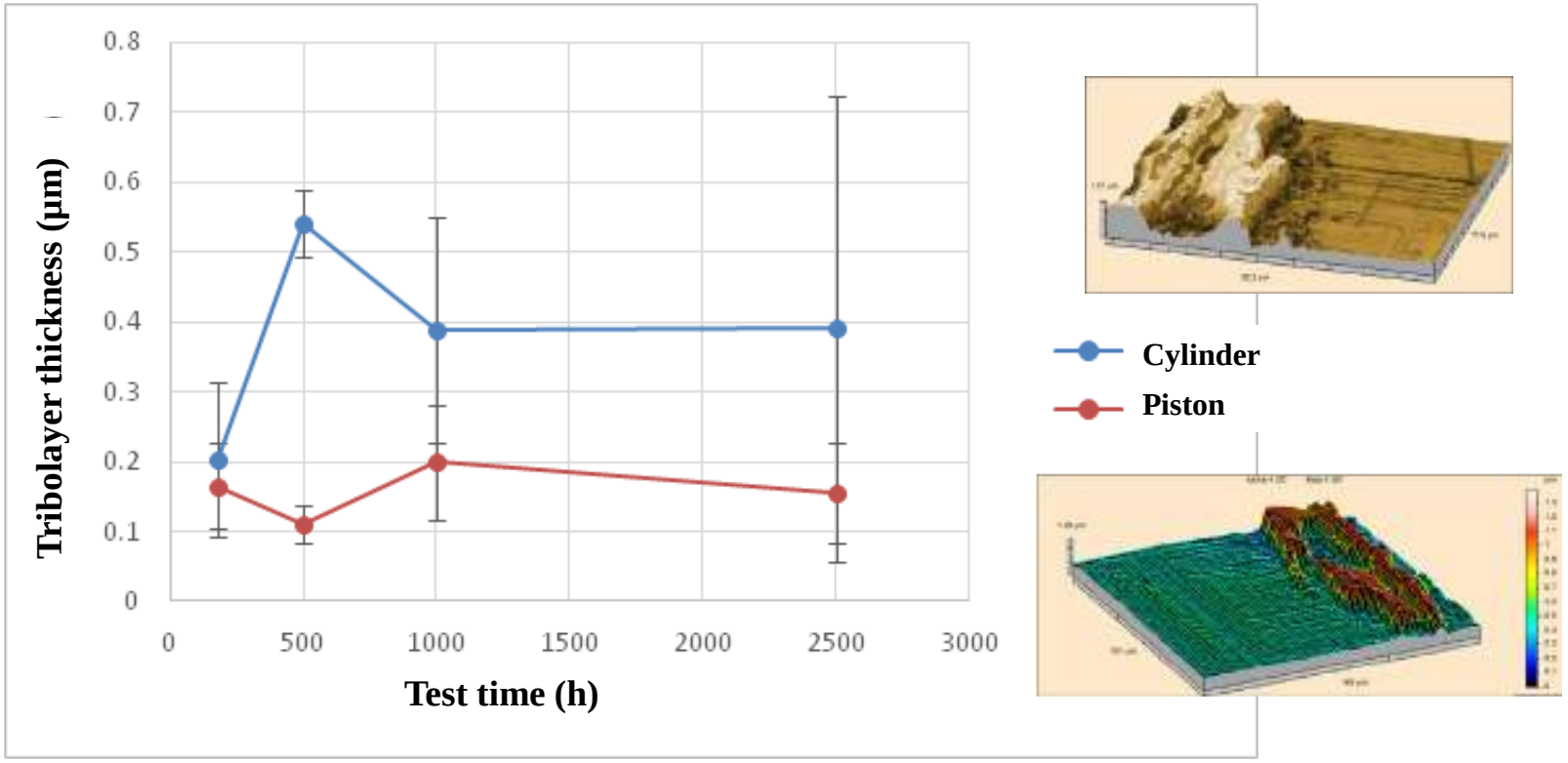



**DLC**
**AISI 304**
**R134a**




*Salvaro, D et al , Genesis and stability of tribolayers in solid lubrication: case of pair DLC-STAINLESS steel, Proceedings of TriboBR2014- Second International Brazilian Conference on Tribology, November 2014, Brazil also Journal of Materials Research Technology, (2015), In press.*

# *Evolution and stability of tribolayers:*



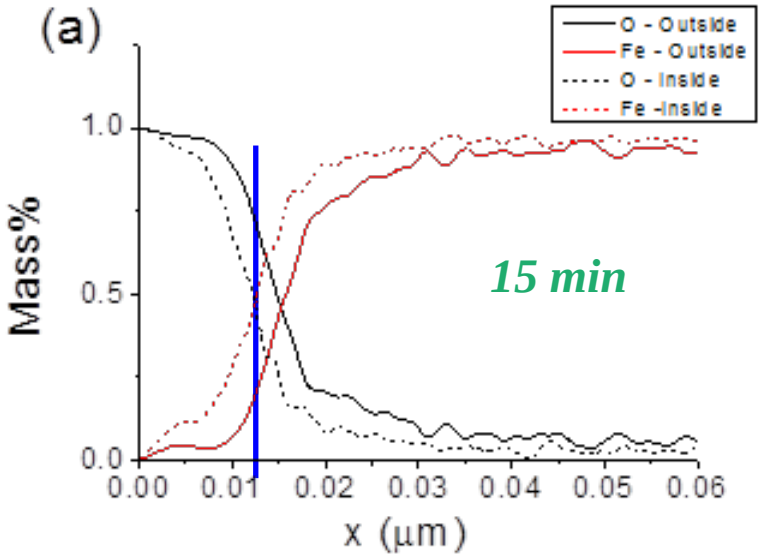


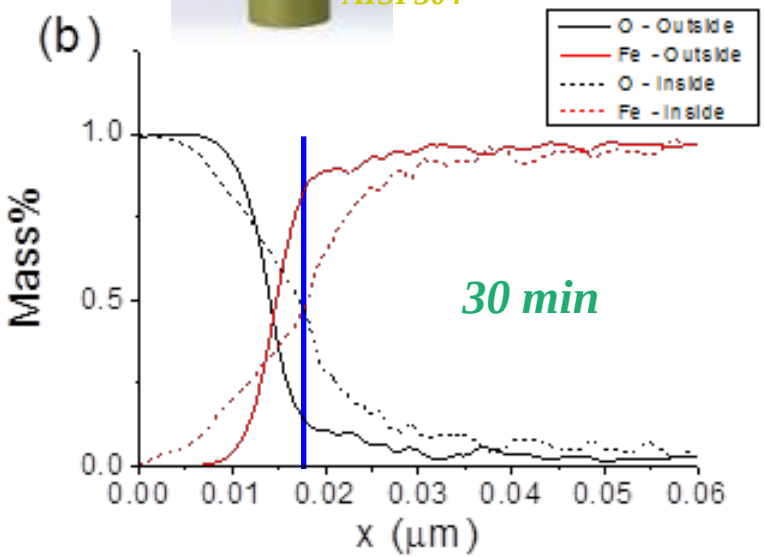


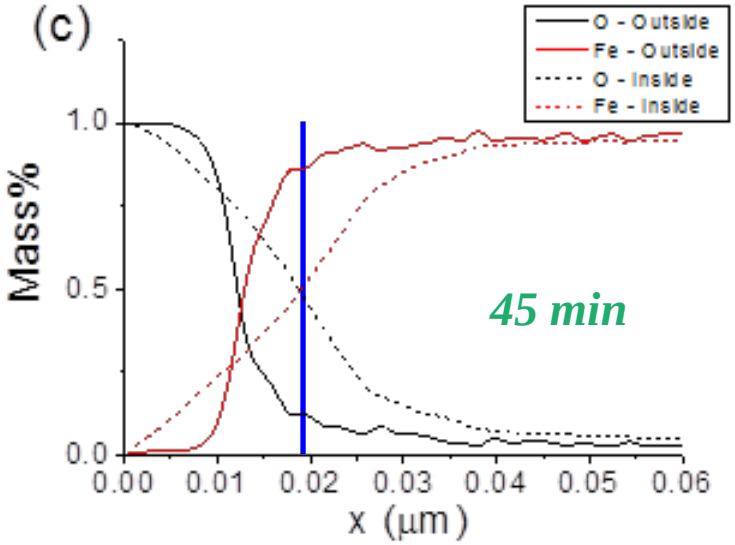

*Salvaro, D et al , Genesis and stability of tribolayers in solid lubrication: case of pair DLC-STAINLESS steel, Proceedings of TriboBR2014- Second International Brazilian Conference on Tribology, November 2014, Brazil also Journal of Materials Research Technology, (2015), In press.*

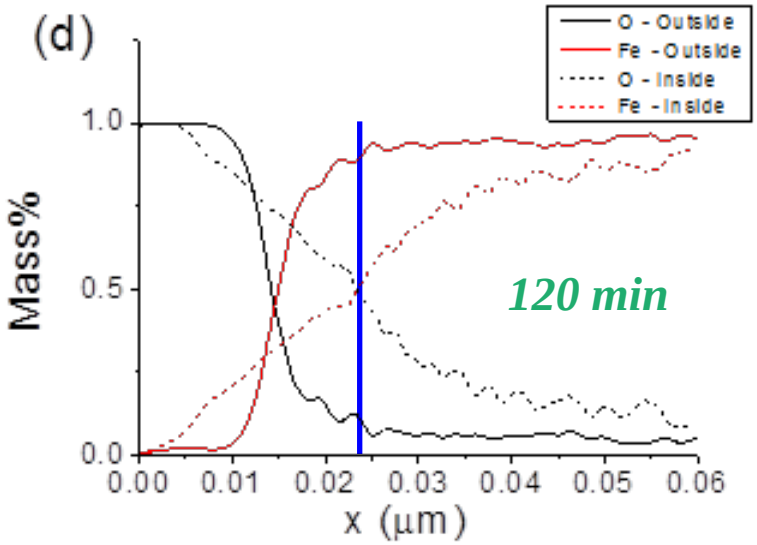
# Evolution and stability of tribolayers: GDOES

DLC
AISI 304



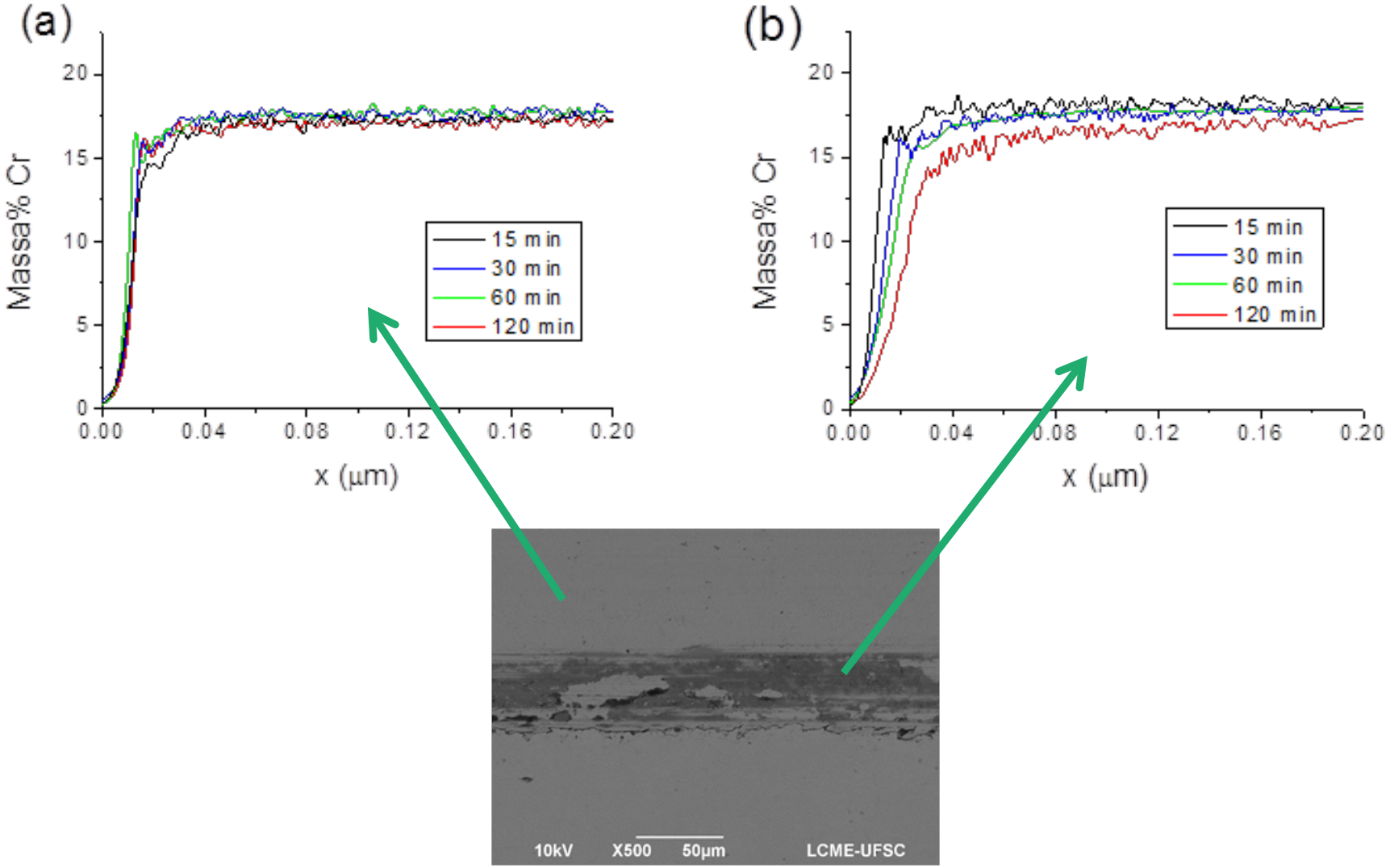




*Barbosa, M.V.; Hammes, G.; Binder, C.; Klein, A. N.; De Mello J. D. B.; Physicochemical characterization of tribolayers by Micro-Raman and GDOES analyses , Tribology International, (2015), v 81, p 223-230.*

# Evolution and stability of tribolayers: GDOES




*Barbosa, M.V.; Hammes, G.; Binder, C.; Klein, A. N.; De Mello J. D. B.; Physicochemical characterization of tribolayers by Micro-Raman and GDOES analyses , Tribology International, v 81, p 223-230, 2015.*

# Nitride Layers:

Process
Characterization

**Sample preparation**

*Topographic:*
- Optical interferometry.

**Nitriding**

*Topographic:*
- Optical interferometry;
- SEM;

*Microstructural:*
- X-ray diffractometry.

**DLC Coating**

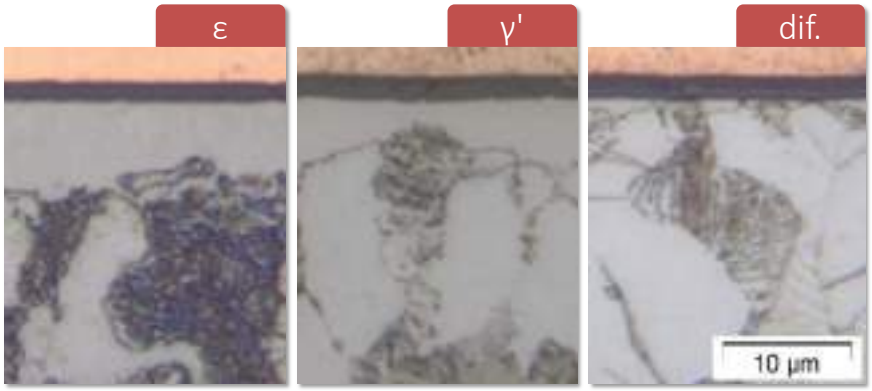
*Topographic:*
- Optical interferometry;
- SEM;

*Microstructural:*
- Transversal section;
- Thickness measurement;

*Mechanical:*
- Microhardness profiling;

*Tribological:*
- Rockwell-C adhesion test;
- Durability test in tribometer.

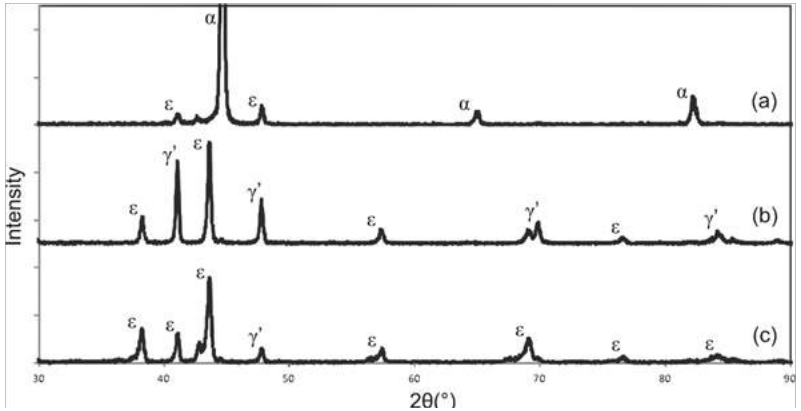
*Wear mechanism:*
- Optical interferometry;
- SEM.




**СНИ®**

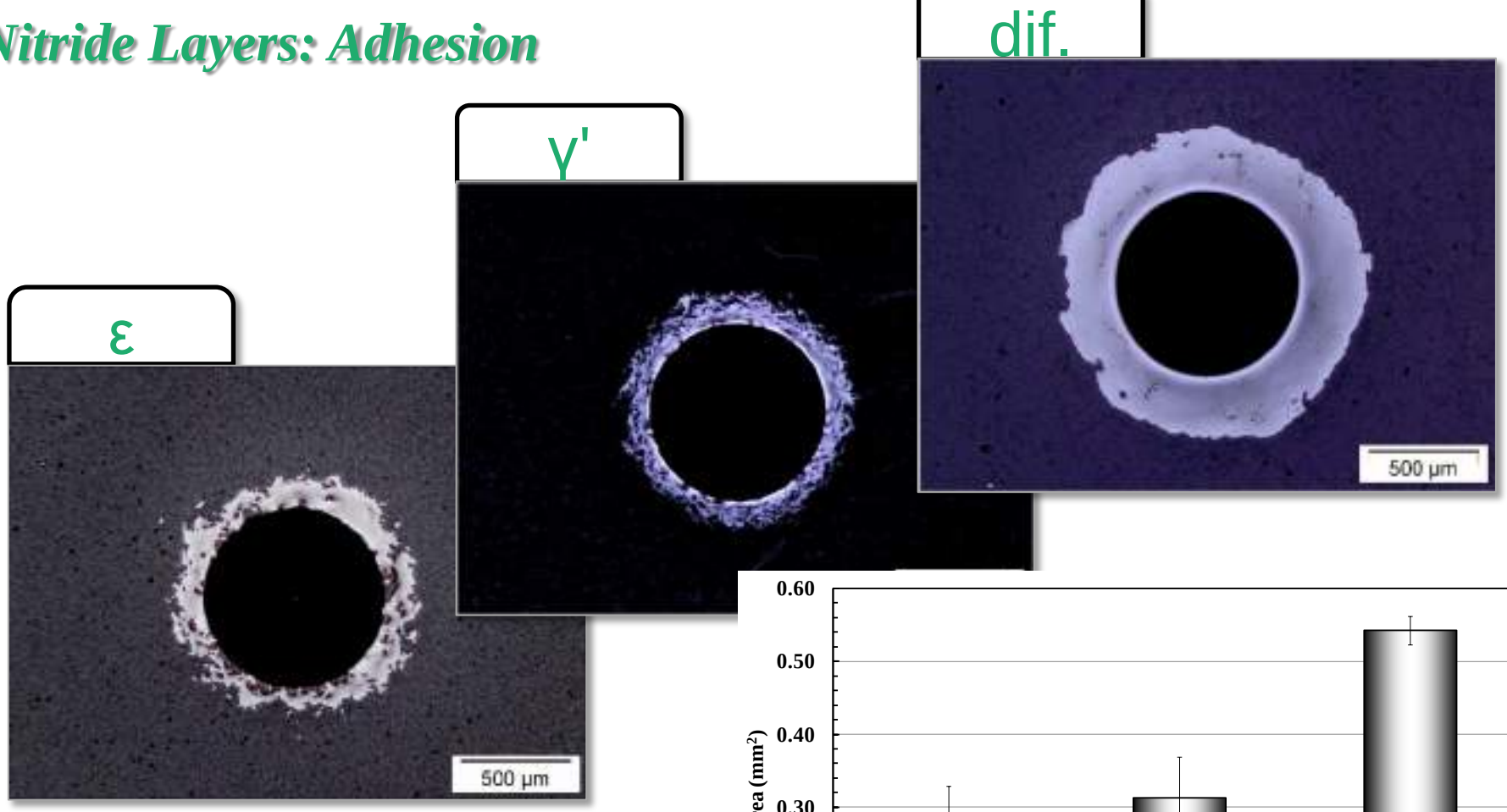
**Patent pending*

| T (°C) | P (Torr) | T (h) | Gas (%) | Phases |
|---|---|---|---|---|
| 550 | 2 | 1.5 | $90N_2$-$9H_2$-$1CH_4$ | ε |
| 570 | 2 | 4.0 | $20N_2$-$80H_2$ | γ’ |
| 480 | 2 | 1.5 | $5N_2$-$95H_2$ | Diffusion |

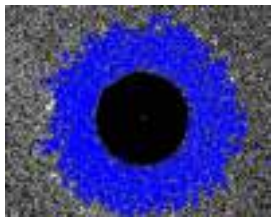


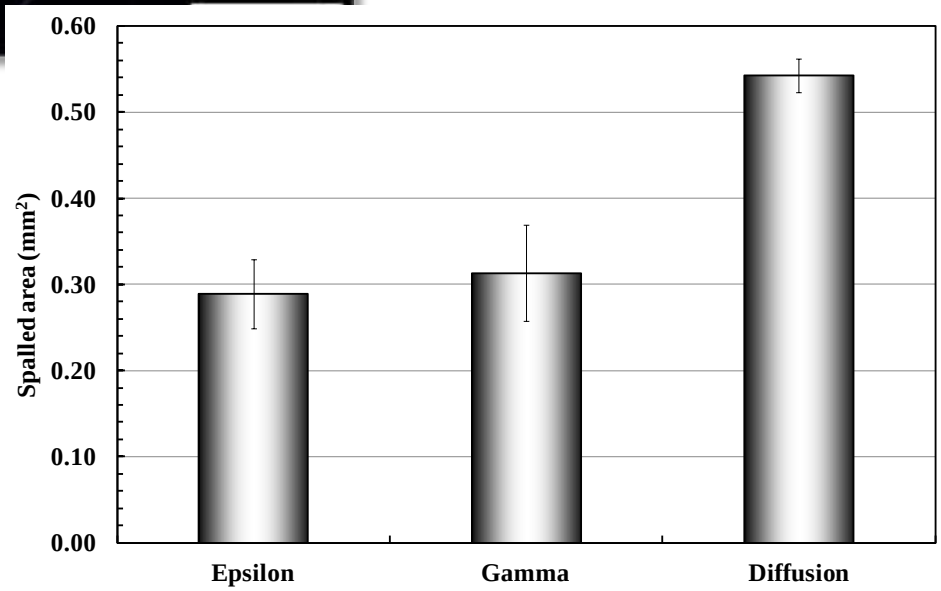

*Shioga, P., Binder, C., Klein, A.N., De Mello, J.D.B., Effect of Different Plasma Nitride Layers on the Tribological Performance of DLC Coatings, Proceedings of the Technical Conference Society of Vacuum Coaters, 2014. Chicago., 2014. Sponsored student.*

# Nitride Layers: Adhesion



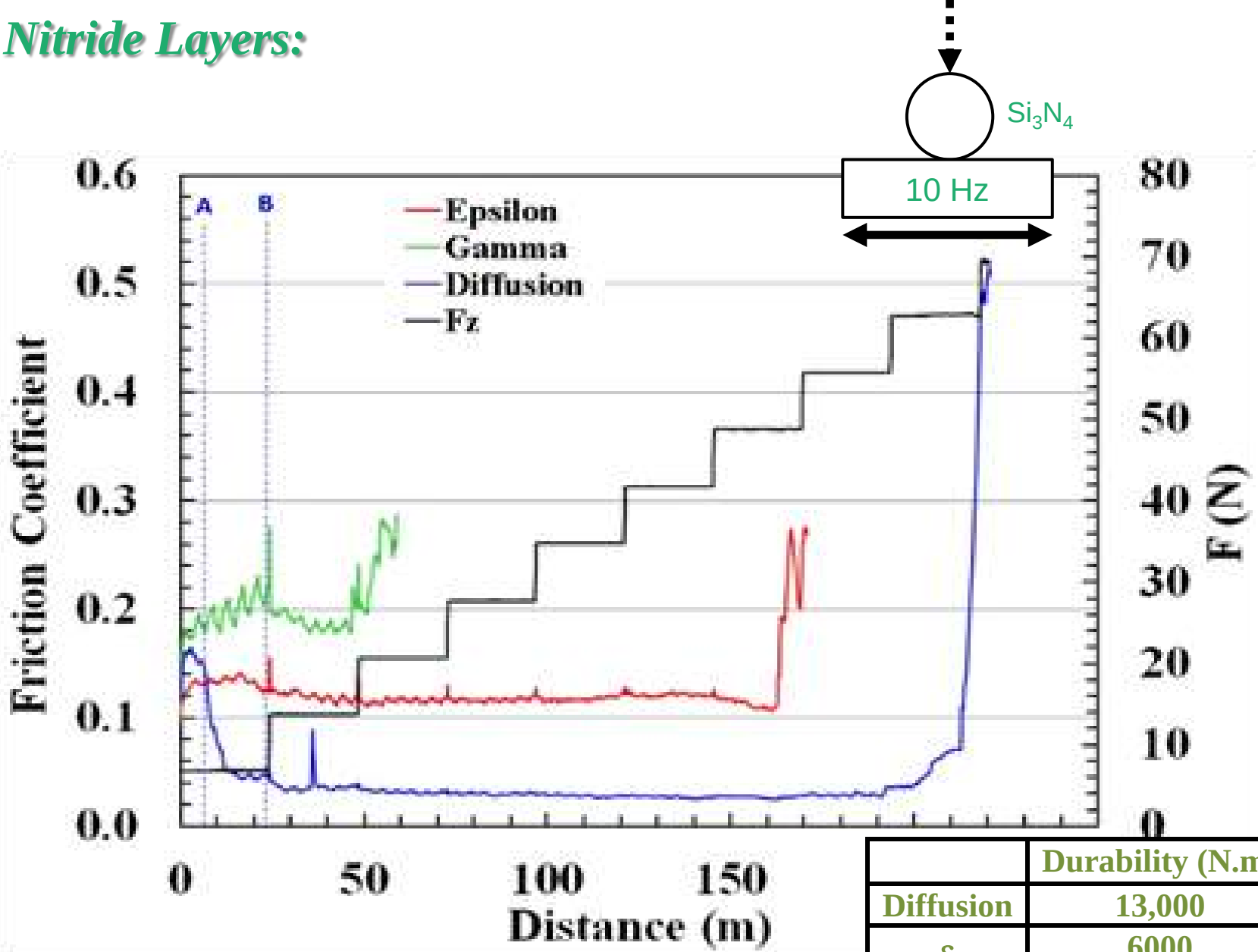

*VDI 3198 + Image analysis*





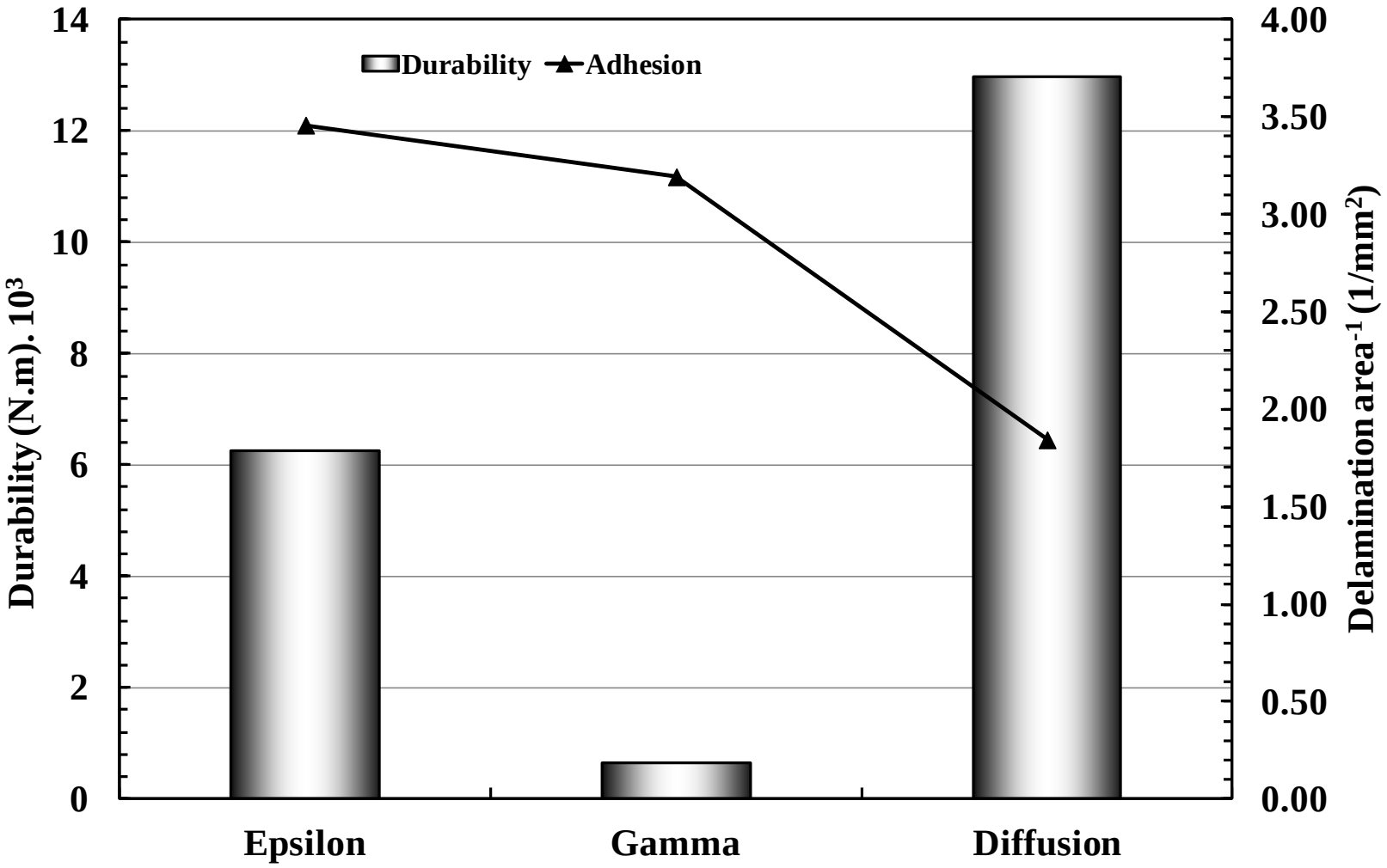

*Shioga, P., Binder, C., Klein, A.N., De Mello, J.D.B., Effect of Different Plasma Nitride Layers on the Tribological Performance of DLC Coatings, Proceedings of the Technical Conference Society of Vacuum Coaters, 2014. Chicago., 2014. Sponsored student.*

# *Nitride Layers:*




| | Durability (N.m) | μ |
|---|---|---|
| Diffusion | 13,000 | 0.05 |
| ε | 6000 | 0.12-0.1 |
| γ' | 600 | 0.2 |

# *Nitride Layers:*




*Shioga, P., Binder, C., Klein, A.N., De Mello, J.D.B., Effect of Different Plasma Nitride Layers on the Tribological Performance of DLC Coatings, Proceedings of the Technical Conference Society of Vacuum Coaters, 2014. Chicago., 2014. Sponsored student.*

## *8000 pistons in a unique thermal cycle*

*EP.2294598 : "Plasma process and reactor for treating metallic pieces"*

MOQUECA TRIBOLÓGICA V.03

# *Concluding Remarks:*

- ✓ *Plant in operation in Monterrey, Mexico;*
- ✓ *600,000 compressores in 2015;*
- ✓ *1,500,000 compressors in two years time (2017).*

# *Thank you !*

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