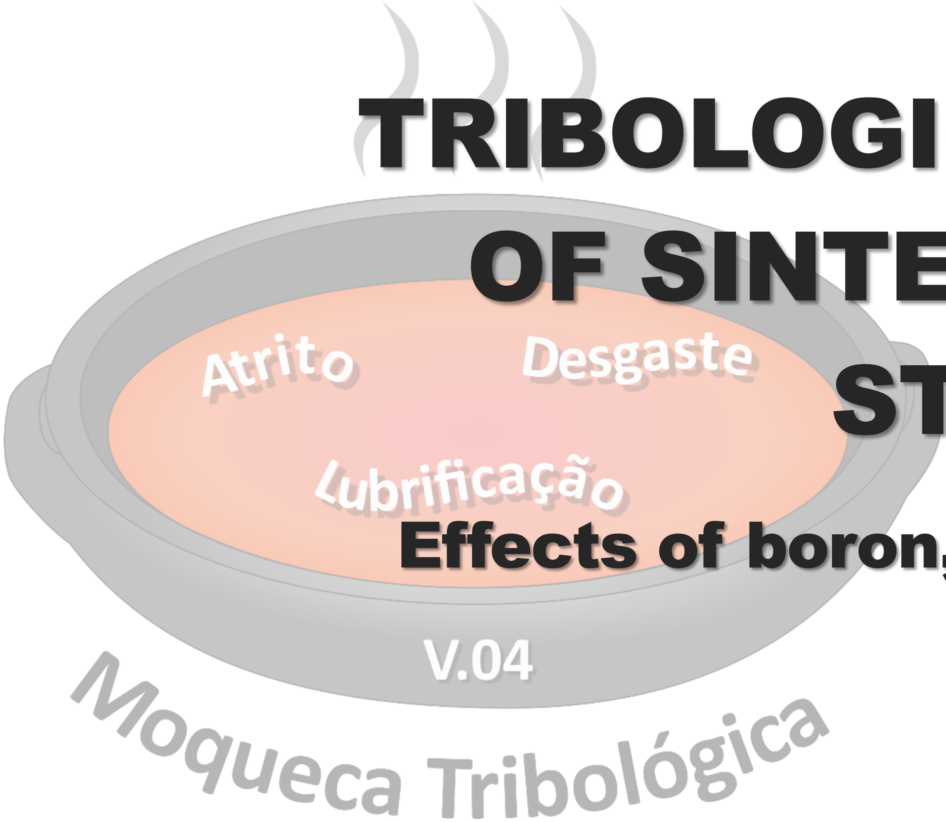

# TRIBOLOGICAL PROPERTIES OF SINTERED AUSTENITIC STAINLESS STEELS

## Effects of boron, yttria, and other additives

**María Cristina Moré Farias**

Programa de Pós-Graduação em Engenharia e Ciência dos Materiais

Universidade de Caxias do Sul

# Profa. María Cristina Moré Farias

- Graduação Eng. Mecânica – ISPJAE - Cuba
- Mestrado Eng. Mecânica – USP
- Doutorado Eng. Mecânica – USP
- Pós-Doutorado Eng. Mecânica – USP
- Docente – PPGMAT/UCS (2010 - atual)

## Principais Pesquisas

- Desenvolvimento e caracterização tribológica materiais sinterizados (metais, cerâmicas) com diferentes aditivos (ativadores, reforços, lubrificantes sólidos)
- Tribologia de materiais de fricção utilizados em freios automotivos
- Determinação de propriedades mecânicas de superfícies empregando indentação instrumentada
- Desenvolvimento de pavimentos cerâmicos base argila com adição de resíduos de rochas

# PPGMAT - UCS

**Programa de Pós-Graduação em Engenharia e Ciência dos Materiais**
**Universidade de Caxias do Sul**

## Docentes 2019

Alexandre Fassini Michels
Carlos Alejandro Figueroa
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Cláudio Antônio Perottoni
Eliena Jonko Birriel
Jadna Catafesta
Janaina da Silva Crespo - Coordenadora
Janete Eunice Zorzi
Larissa Nardini Carli
Marcelo Giovanela
Márcio Ronaldo Farias Soares
Maria Cristina Moré Farias
Mariana Roesch Ely
Otávio Bianchi
Robinson Carlos Dudley Cruz
Sidnei Moura e Silva
Thiago Barcellos da Silva

Professores PPGMAT 2019

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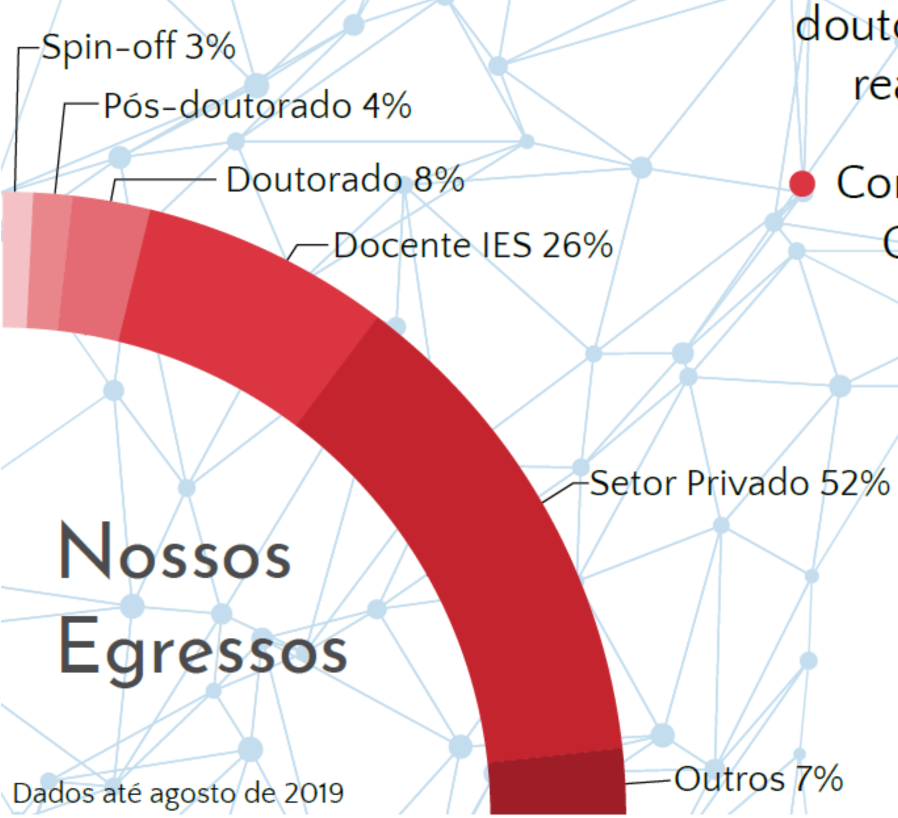
# PPGMAT - UCS

## NÚMEROS

- Corpo discente 2019: 17 alunos de mestrado e 26 de doutorado, além de estudantes de graduação realizando trabalhos de iniciação científica.
- Corpo docente permanente: 75% têm bolsa CNPq de Produtividade em Pesquisa, que distingue os pesquisadores com alta produtividade.
- 129 mestres formados.
- 24 doutores formados.
- 45 patentes.
- 570 artigos.



Nossos Egressos

Dados até agosto de 2019

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# PPGMAT - UCS

## LINHA DO TEMPO

**2003**
- Prof. Israel J. R. Baumvol é convidado a criar um Programa de Pós-Graduação em Materiais

**2004**
- Início das atividades do PPGMAT com 85 inscritos para 15 vagas

**2005**
- Primeira defesa de Mestrado, pela tecnóloga em Polímeros Maira Finkler

**2006**
- Convênio UCS-SIMECS para complementar recursos públicos para laboratório do PPGMAT

**2007**
- Inauguração do Laboratório de Engenharia de Superfícies e Tratamentos Térmicos (LESTT)
- Início do Doutorado Interinstitucional PGCIMAT/UFRGS - PPGMAT/UCS
- Inauguração do Laboratório de Caracterização de Materiais I

**2008**
- O PPGMAT compõe a recém criada "Área de Materiais" da CAPES
- Inauguração do Núcleo de Pesquisas em Geoquímica (NupGeo)

**2009**
- Criação do Instituto Nacional de Engenharia de Superfícies (INES)
- Convênio UCS-CIC para complementar recursos públicos ao laboratório do INES
- Início das atividades do Laboratório de Pesquisa em Química dos Materiais (LPQM)

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# PPGMAT - UCS

**2013**

- O PPGMAT obtém nota 5 na avaliação trienal da CAPES
- Inauguração do Laboratório de Caracterização de Materiais para Mineração

**2014**

- Inauguração do Laboratório de Reologia
- O IMC integra a rede de laboratórios associados ao INMETRO para Inovação
- Comemoração dos 10 anos do PPGMAT, com palestra do professor Deniol Tanaka

**2015**

- Inauguração do Laboratório Central de Microscopia Prof. Israel Baumvol
- Segunda Edição do Brafitec 2015-2018

**2016**

- Primeira defesa de Doutorado do PPGMAT de Ana Cláudia Rangel Faria
- Primeira cerimônia de Titulação da Pós-Graduação

**2017**

- Assinatura de Convênio de Consolidação de Internacionalização com Lodz University of Technology

**2018**

- Participação no Fórum BRAFITEC com visitação a instituições parceiras.

**2019**

- Assinatura de convênios interncionais - Programa Erasmus+ e Athlone Institute of Technology

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# Sintered austenitic stainless steels

- Stainless steels have been successfully fabricated through different powder metallurgy (P/M) routes
- Austenitic (ASS) and ferritic (FSS) stainless steels are the most widely produced by P/M
- ASS exhibit a good combination of corrosion and oxidation resistance, associated with good mechanical properties
- Interest in P/M SS for general use (biomedical, dental, chemical, nuclear, automotive, aerospace) has increased

# Sintered austenitic stainless steels

- P/M ASS present lower mechanical resistance than the wrought or cast steels, due to their intrinsic porosity
- Applications of ASS are also limited by their relative softness and susceptibility to wear (adhesive, abrasive, fatigue) and wear-corrosion
- Three routes have been implemented to improve density and reach a good combination of mechanical, wear and corrosion properties of P/M SS

  i. surface modification of the sintered body by plasma-assisted surface treatments

  ii. modification of parameters in compaction and sintering steps

  iii. addition of certain elements (sintering enhancers or activators and reinforcements)

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# Activated sintering

- **Activated sintering refers to any special process which results in an increased sintering rate or densification rate, i.e.,**
  - promotes lowering sintering temperature; shorten sintering time or improve sintered properties
- **Sintering enhancement approaches**
  - Solid state activated sintering
  - Liquid phase sintering
- **Sintering activators**
  - small particles, frequently used in low concentrations
  - promote effective changes in interfacial energy, grain boundary mobility, reduction of void fraction, diffusion rates, and phase stability

*R. M. German & B. H. Rabin (1985) Powder Metallurgy, 28:1, 7-12.*

# Possible routes to alter sintering rate

- **Change process conditions (particle size or temperature)**
- **Change defects configuration by pretreating powders (alloying or deformation)**
- **Application of external force (Ex. HP, HIP)**
- **Promote the formation of second phases that act as preferential diffusion paths**
  - Solid state activated sintering
  - Liquid phase sintering

*R. M. German & B. H. Rabin (1985) Powder Metallurgy, 28:1, 7-12.*

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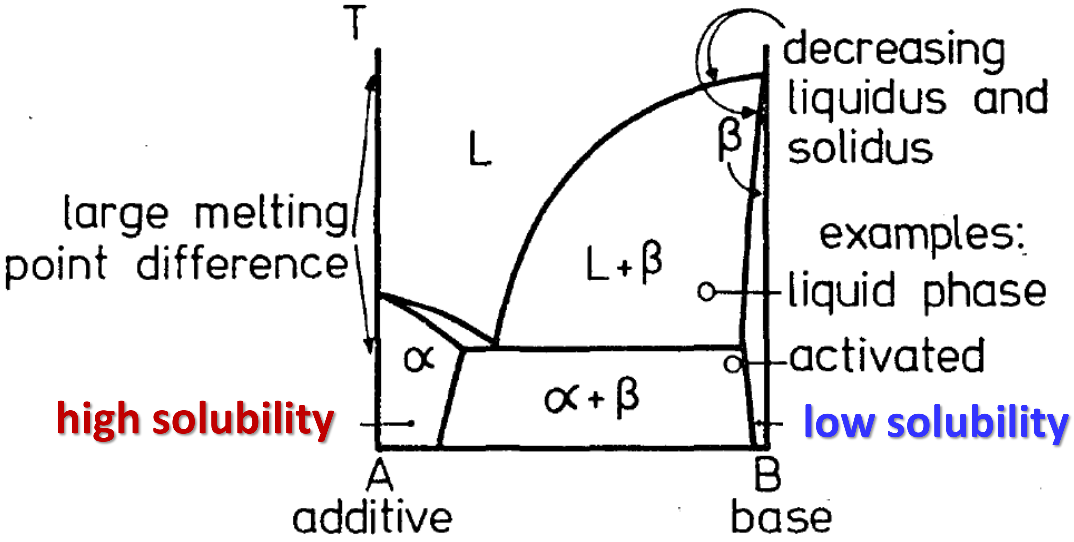
# Liquid phase sintering

- **In the case of liquid-phase sintering, densification is achieved through the formation of a system with high wettability between the matrix and the liquid phase**
  - improves the mass transfer rate
  - Increase the sintering rate by decreasing sintering temperature or reducing sintering time
- **Liquid phase can be obtained by**
  - **addition of low melting temperature elements**
    - Cu, P, Si, Cu-10Sn, Tin, Babbitt
  - **dissociation of a mixture containing the base material and additive powders in a new phase with eutectic composition**
    - B, $Cr_2B$, FeB, $Fe_2B$

*R. M. German & K. A. D'Angelo (1984), International Metals Reviews, 29:1, 249-272.*

# Criteria for selecting sintering additive

- **Solubility: $S_B/S_A > 1$**
  - Favorable effect in diffusion rate
    - ❑ diffusive flux in additive layer
    - ❑ favorable change in bonding free energy
    - ❑ good wetting and adhesion of additive to base material



*Idealized phase diagram showing characteristics most favorable for enhanced sintering*

R. M. German & K. A. D'Angelo (1984), *International Metals Reviews*, 29:1, 249-272.

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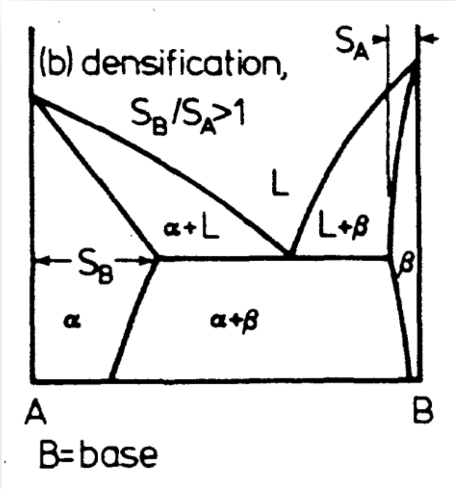
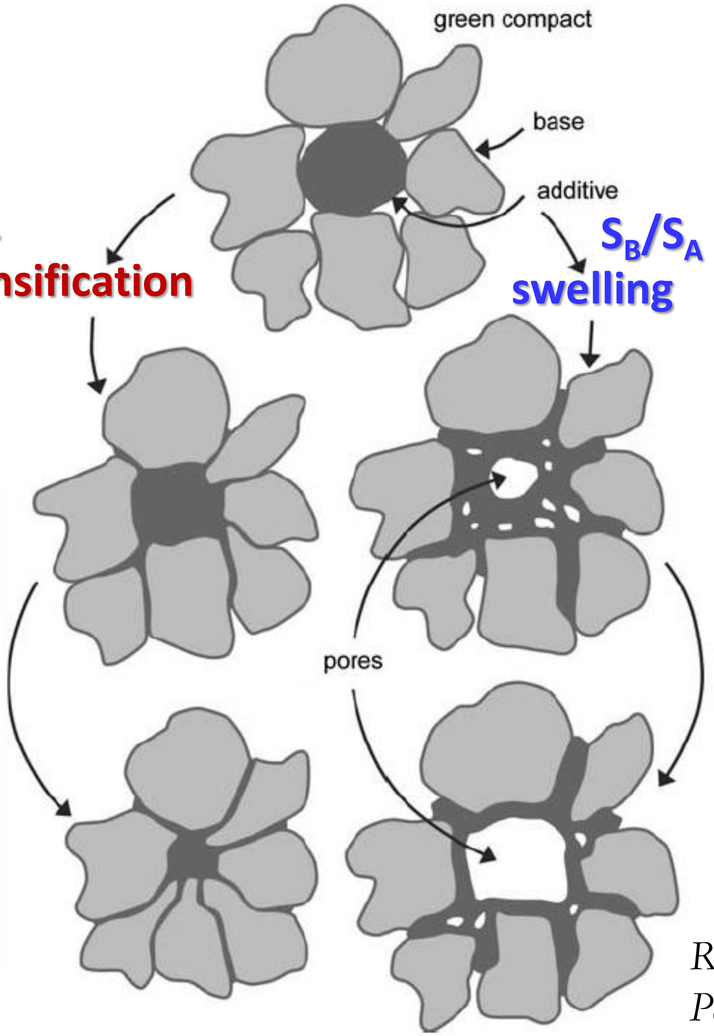
# Criteria for selecting sintering additive



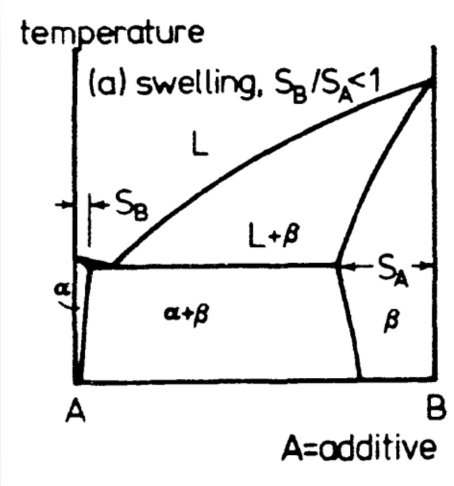
**$S_B/S_A$ > 1**

**densification**



**$S_B/S_A$ < 1**

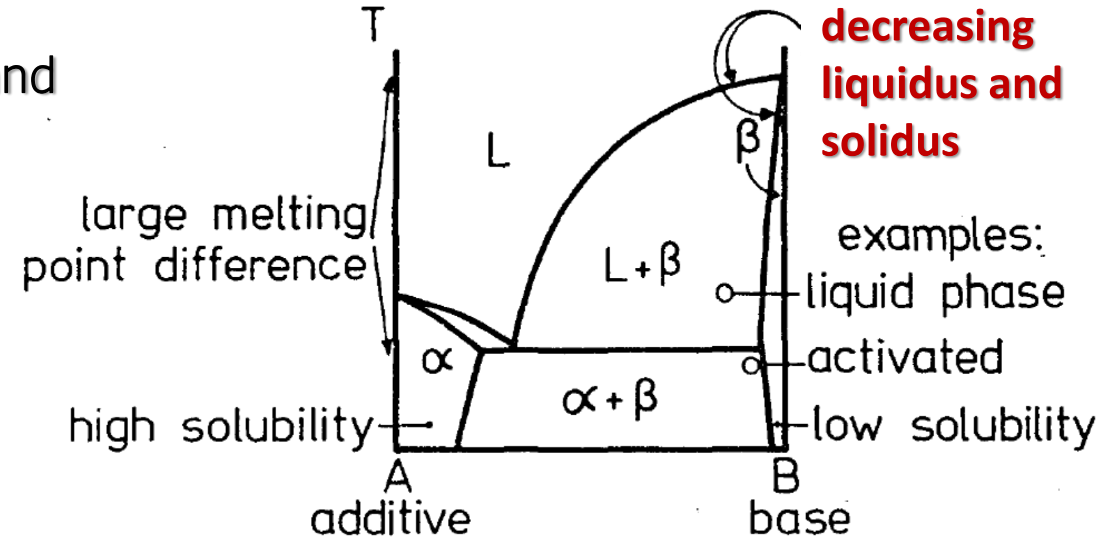
**swelling**



*R. M. German & B. H. Rabin (1985)*
*Powder Metallurgy, 28:1, 7-12.*

# Criteria for selecting sintering additive

- **Segregation: $T_{mB}/T_{LP} > 1$**
  - Segregation of an equilibrium second phase at interparticle site
    - ❑ Decreasing liquidus and solidus as A is increased

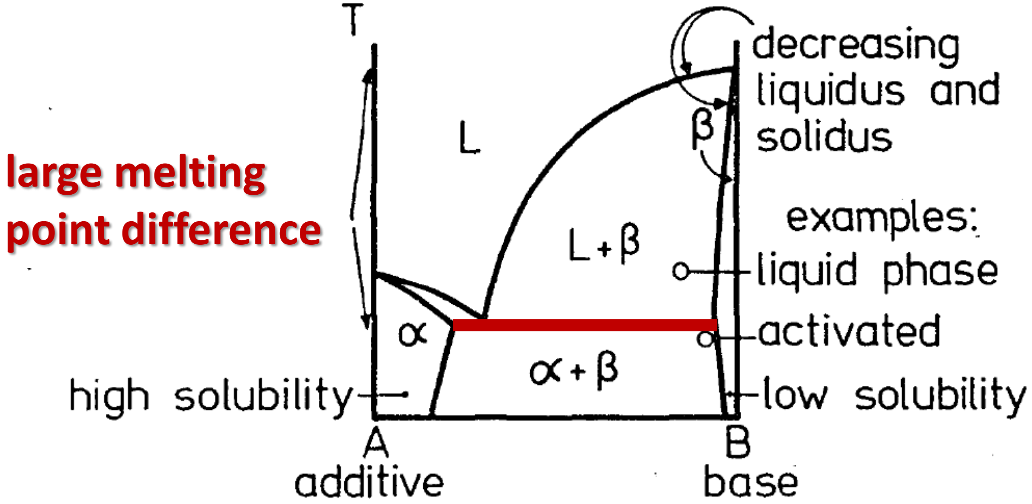


**decreasing liquidus and solidus**

*R. M. German & B. H. Rabin (1985) Powder Metallurgy, 28:1, 7-12.*

# Criteria for selecting sintering additive

- **Diffusion: $D_E/D_B > 1$**
  - $D_E$: diffusivity of B in A layer
  - $D_B$: selfdiffusivity of B
  - additive flows to the interparticle boundary
  - rapid diffusion along the sinter bond
  - low liquid temperature for A
    - ☐ low activation energy
    - ☐ high diffusivity


**large melting point difference**

*R. M. German & B. H. Rabin (1985) Powder Metallurgy, 28:1, 7-12.*

# Sintering additives for ferrous powders

- **Sintering activators**
  - C, B, P,
  - Cu, Sn, S, Ni, Mn, Co, Ti
- **Other additives**
  - $Al_2O_3$, $Y_2O_3$
  - $B_2Cr$, $Cr_2Al$, $TiCr_2$, TiAl
  - VC, SiC, TiC
  - $TiB_2$

*R. M. German & K. A. D'Angelo (1984), International Metals Reviews, 29:1, 249-272.*
*Oke, S.R., Ige, O.O., Falodun, O.E. et al. (2019) Int J Adv Manuf Technol, 102, 3271–3290.*

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# Other sintering additives

- **In combination with solid state or liquid phase sintering activators, other elements have been added to**
  - **enhance mechanical properties**
  - **improve corrosion and high-temperature oxidation resistance**
  - **reduce friction and wear**
- **Low matrix-additive interaction makes necessary the use sintering activators**
  - **Solid lubricants (h-BN, $MoS_2$)**
  - **Reinforcement**
    - ☐ Oxide ceramics ($Al_2O_3$, $Y_2O_3$) → mechanical properties, wear and corrosion resistance
    - ☐ Intermetallics ($Cr_2Al$, $TiCr_2$, TiAl) → mechanical, corrosion and wear properties
    - ☐ Carbides (VC, SiC, TiC) → mechanical properties, wear resistance
    - ☐ Borides ($TiB_2$) → mechanical and tribological properties
- **The improvement of mechanical, corrosion and tribological properties of the composites depends on the amount, size, shape and distribution of the dispersed second phase particles, and P/M parameters**

*Oke, S.R., Ige, O.O., Falodun, O.E. et al. (2019) Int J Adv Manuf Technol, 102, 3271–3290.*

# Tribology properties of sintered austenitic stainless steels

- **The literature on the tribological properties of P/M austenitic stainless steels and theirs composites is scarce**
- **There exist some researches on dry sliding behavior of sintered austenitic stainless steels added with**
  - Metals or metallic alloys: B, Cu-Sn
  - Borides: $TiB_2$
  - Nitrides: BN
  - Oxides: $Al_2O_3$, $Y_2O_3$, YAG
  - Carbides: SiC, VC
  - Intermetallics: $TiCr_2$, $Cr_2Al$, $Ni_3Al$, $Fe_3Al$

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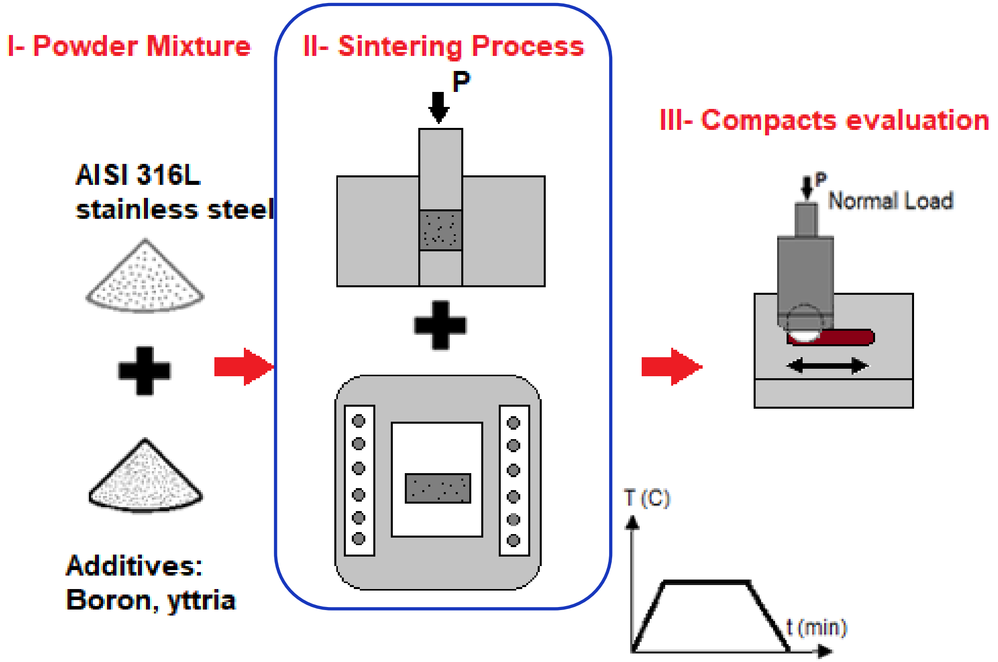
# Metal matrix composites (MMC)



I- Powder Mixture

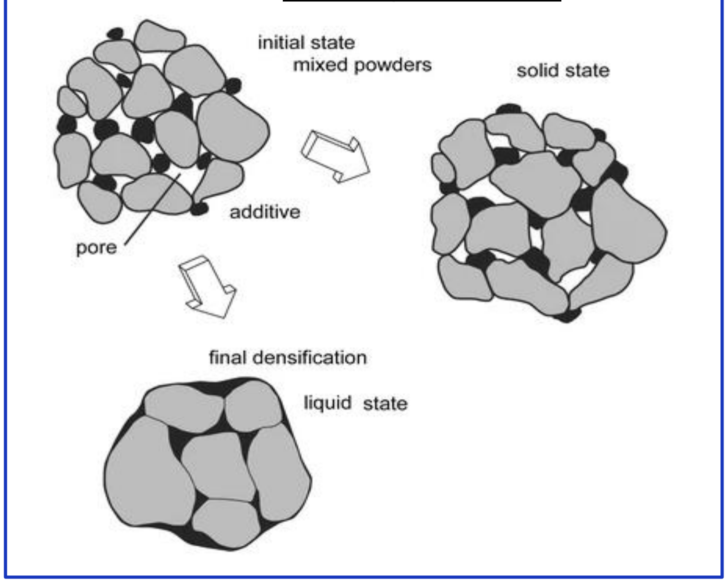
AISI 316L stainless steel

Additives: Boron, yttria

II- Sintering Process

III- Compacts evaluation

**Sintering mechanism**



*Ref: German et al Review: liquid phase sintering. J Mater Sci (2009) 44:1–39*

**Powder metallurgy**

- Effect of sintering parameters as temperature on the sintered phase transformation
- Importance of the particles: size, shape and volume fraction
- Effect of mixture of different materials

**Secondary particle additives**

Sintering mechanism

- Liquid phase sintering
- Solid phase sintering

**Final Properties**

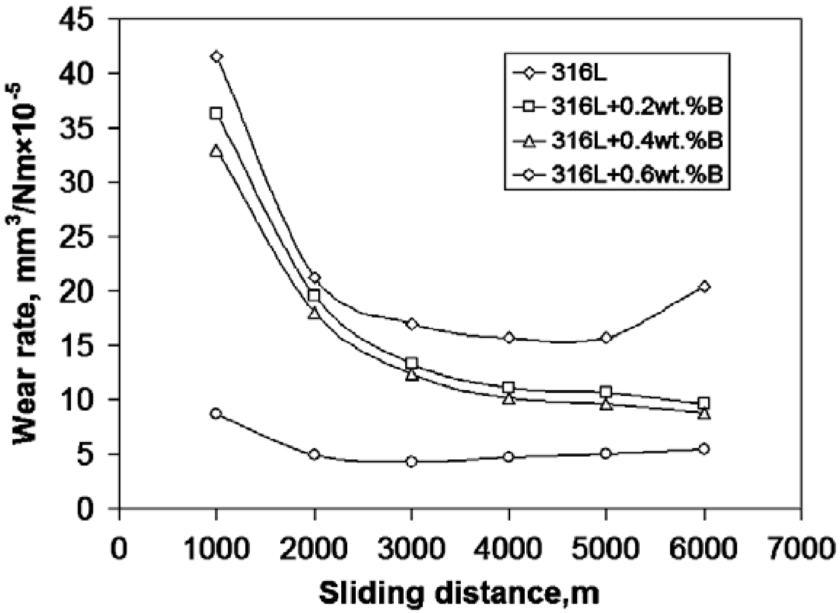
- Higher hardness and density
- Oxidation resistance
- Wear resistance

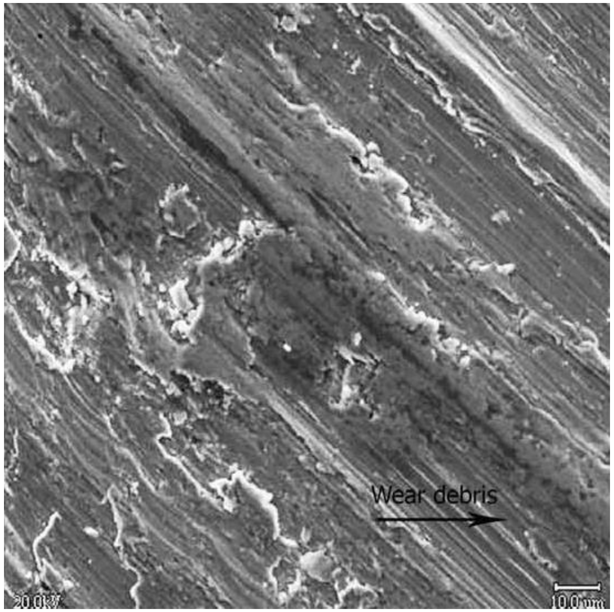
# Sintered Austenitic Stainless Steel

## Precedents

- D. Uzunsoy, *Investigation of dry sliding wear properties of boron doped powder metallurgy 316L stainless steel*, ***Mater. Des.*** 31 (8) (2010) 3896–3900.
- M. Vardavoulias, M. Jeandin, F. Velasco, J.M. Torralba, *Dry sliding wear mechanism for P/M austenitic stainless steels and their composites containing* $Al_2O_3$ *and* $Y_2O_3$ *particles*, ***Tribol. Int.*** 29 (6) (1996) 499–506.
- A. Bautista, F. Velasco, J. Abenojar, *Oxidation resistance of sintered stainless steels: effect of yttria additions*, ***Corros. Sci.*** 45 (2003) 1343–1354.

# Dry sliding wear of boron doped P/M ASS (Uzunsoy, 2010)





- Boron additions decrease plastic deformation and wear rate in sliding contact
- Hardness and porosity level have a significant effect on the wear behavior of P/M ASS

# Sliding wear mechanism for P/M ASS and their composites (Vardavoulias et al., 1996)

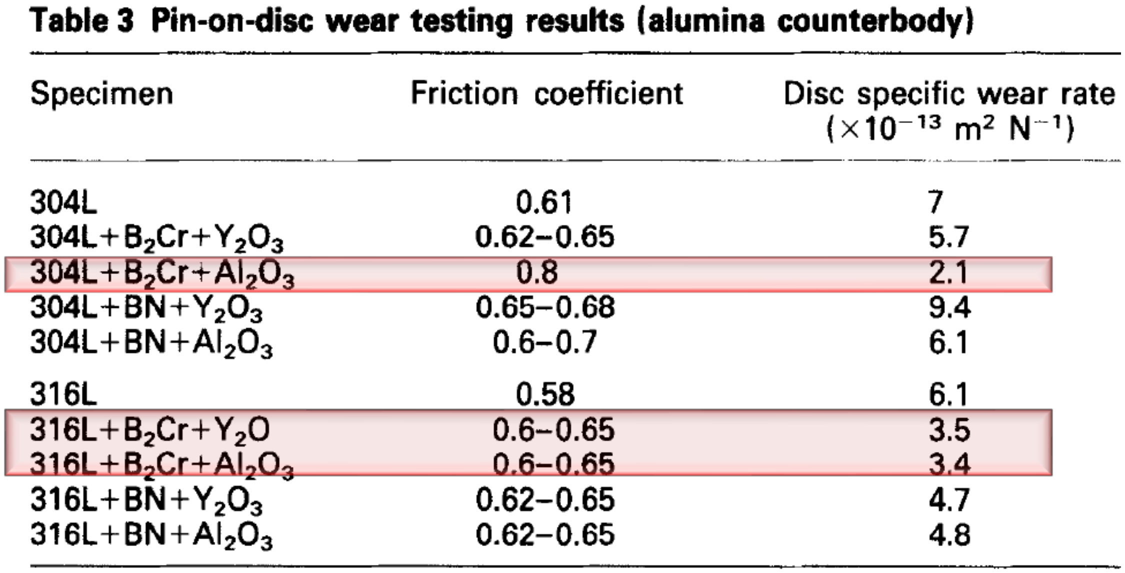
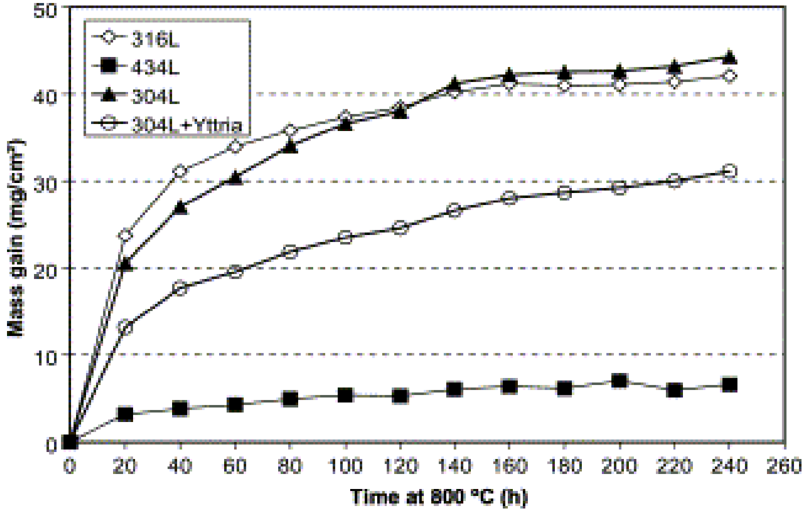


**Table 3 Pin-on-disc wear testing results (alumina counterbody)**

| Specimen | Friction coefficient | Disc specific wear rate ($\times 10^{-13}$ $m^2$ $N^{-1}$) |
|---|---|---|
| 304L | 0.61 | 7 |
| $304L+B_2Cr+Y_2O_3$ | 0.62–0.65 | 5.7 |
| $304L+B_2Cr+Al_2O_3$ | 0.8 | 2.1 |
| $304L+BN+Y_2O_3$ | 0.65–0.68 | 9.4 |
| $304L+BN+Al_2O_3$ | 0.6–0.7 | 6.1 |
| 316L | 0.58 | 6.1 |
| $316L+B_2Cr+Y_2O$ | 0.6–0.65 | 3.5 |
| $316L+B_2Cr+Al_2O_3$ | 0.6–0.65 | 3.4 |
| $316L+BN+Y_2O_3$ | 0.62–0.65 | 4.7 |
| $316L+BN+Al_2O_3$ | 0.62–0.65 | 4.8 |

- Ceramic particles ($Al_20_3$ and $Y_20_3$) and sintering activators ($B_2Cr$, BN) improved wear resistance
- Ceramic particles limited plastic deformation while sintering activators decreased porosity
- Friction coefficient did not vary substantially (0.6 and 0.7)
- “Friction-induced martensite” (debris)

# Oxidation resistance of sintered stainless steels **(Bautista et al., 2003)**



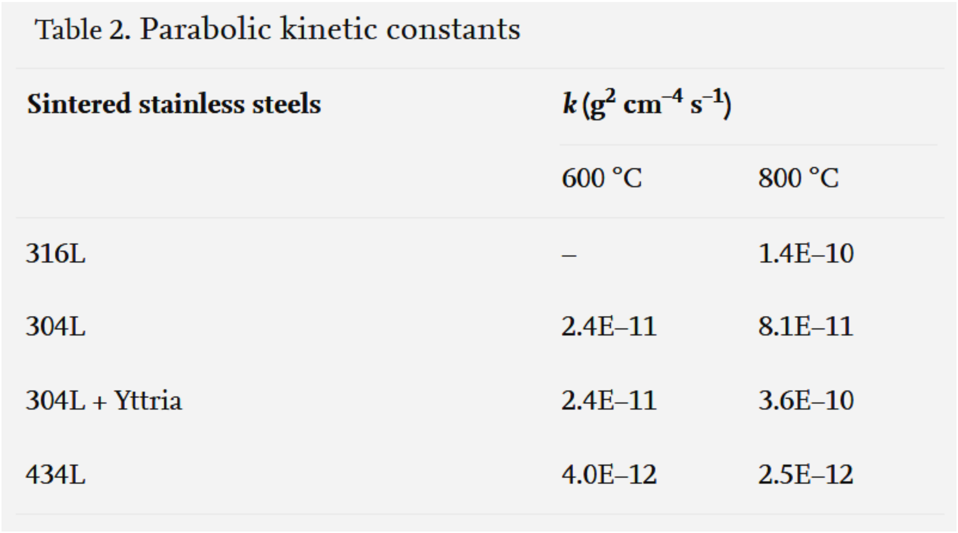


Table 2. Parabolic kinetic constants

| **Sintered stainless steels** | ***k*** **(g$^2$ cm$^{-4}$ s$^{-1}$)** | |
|---|---|---|
| | 600 °C | 800 °C |
| 316L | – | 1.4E–10 |
| 304L | 2.4E–11 | 8.1E–11 |
| 304L + Yttria | 2.4E–11 | 3.6E–10 |
| 434L | 4.0E–12 | 2.5E–12 |

# Sintered Austenitic Stainless Steel – recent results

- ❖ **Friction and wear**
- ❖ **High-temperature oxidation**

**Effect of boron and yttria additions**

**Team**

Profa. M. Cristina Moré Farias

Postgraduate students
Collaborators professors

- Serafini, F.L., Peruzzo, M., Krindges, I., Ordoñez, M.F.C., Rodrigues, D., Souza, R.M., Farias, M.C.M. (2019) ***Materials Characterization***, 152, pp. 253-264.
- Peruzzo, M., Serafini, F.L., Ordoñez, M.F.C., Souza, R.M., Farias, M.C.M. (2019) ***Wear***, 422-423, pp. 108-118.
- Peruzzo, M., Beux, T.D., Ordoñez, M.F.C., Souza, R.M., Farias, M.C.M. (2017) ***Corrosion Science***, 129, pp. 26-37.
- Serafini, F. L. ; Peruzzo, M. ; Beux, T. D. ; Ordoñez, M.F.C. ; Dotta, A. L. B. ; Souza, R.M. ; Farias, M.C.M. In: 6th World Tribology Congress, WTC2017, Beijing. ***6th World Tribology Congress***, WTC2017, 2017.

## Further studies for P/M ASSs and their composites

- ➢ Friction and wear at high-temperature
- ➢ Tribocorrosion behavior

# P/M processing of ASS 316L

0.6 wt% powder boron → Powder AISI 316L ← 0.8 wt% powder boron

↓

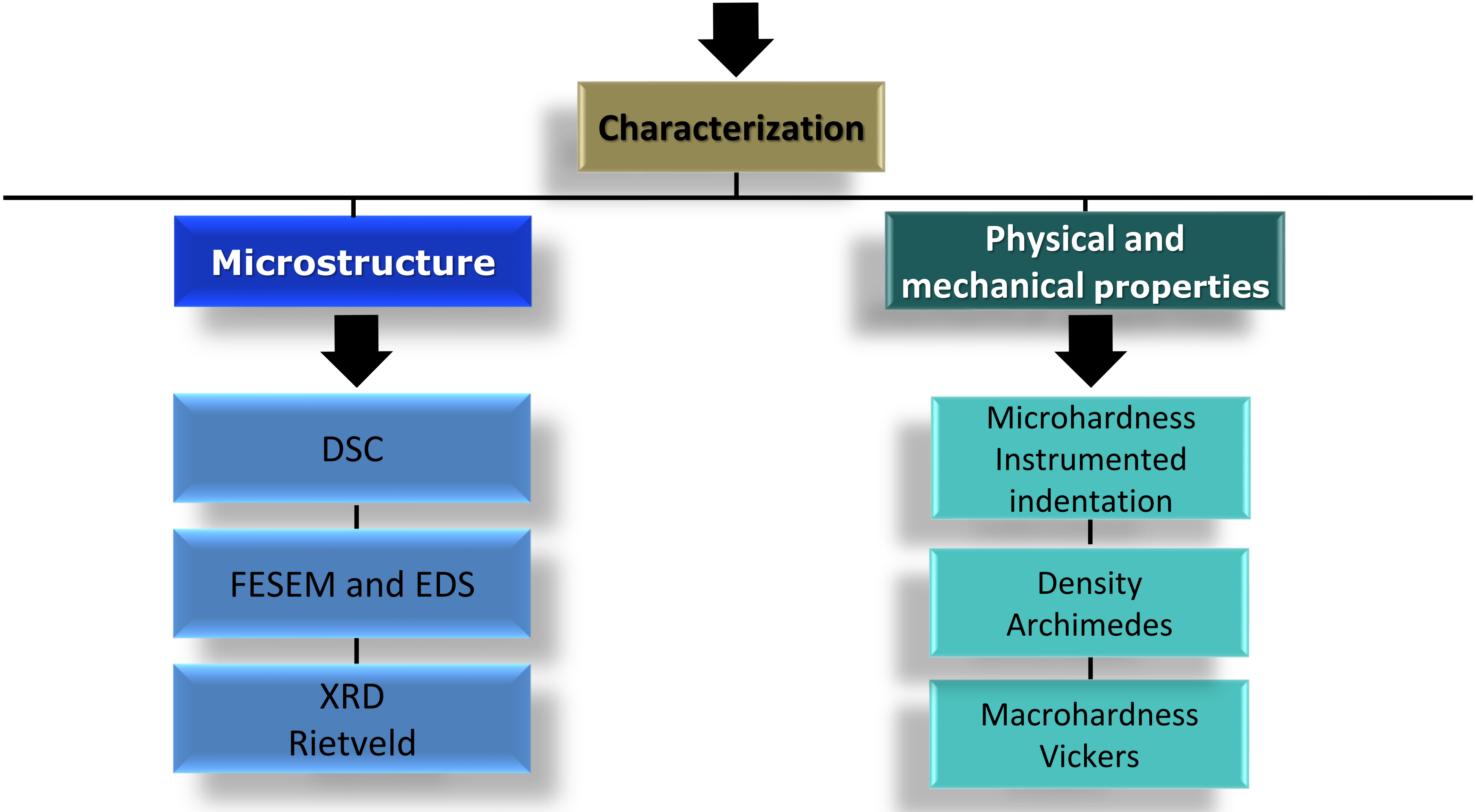
Sintering process of powder mixture

- Uniaxial compression 800 MPa
- Heating rate 10°C/min
- Atmosphere Argon
- Temperature 1240°C 30 min

*BRATS - Sintered Filters Special Metallic Powders (Cajamar, Sao Paulo, Brazil)*

*mcmfarias@ucs.br*

# Initial characterization of the sintered ASS 316L samples



**Characterization**

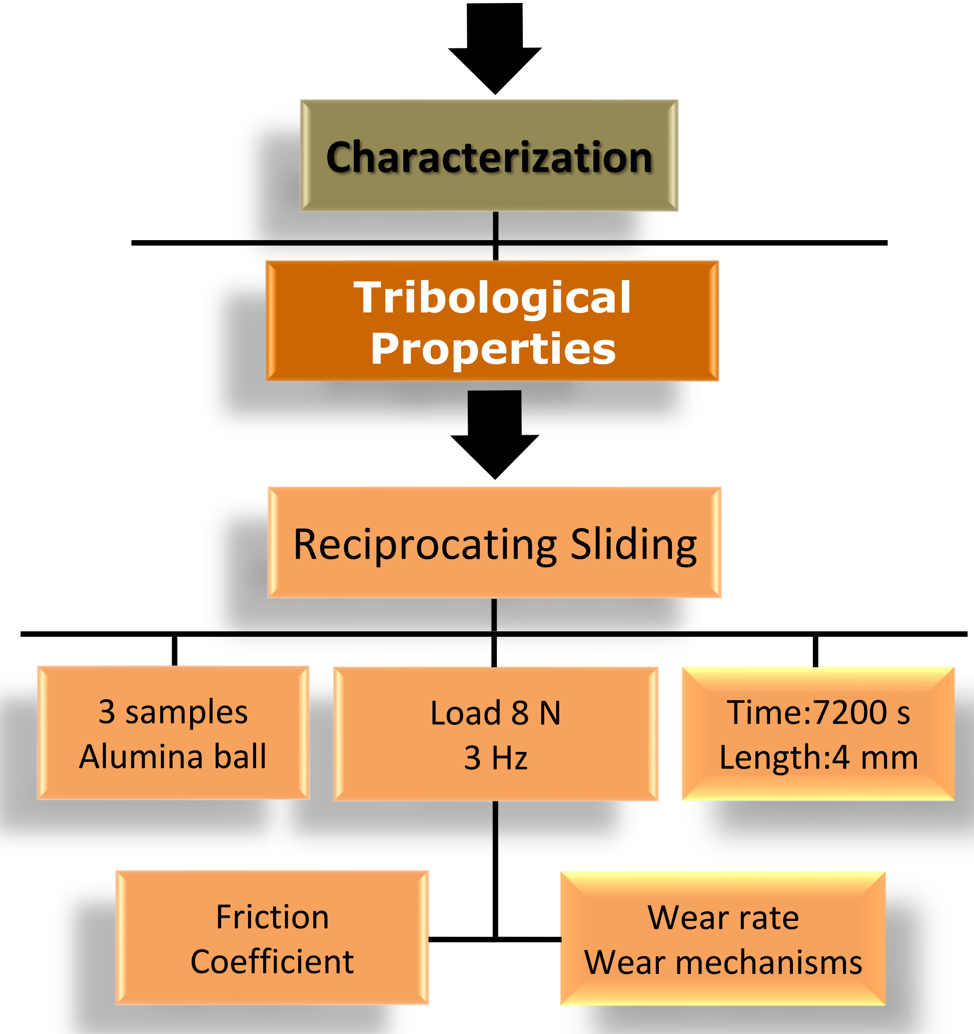
**Microstructure**

- DSC
- FESEM and EDS
- XRD Rietveld

**Physical and mechanical properties**

- Microhardness Instrumented indentation
- Density Archimedes
- Macrohardness Vickers

# Tribological characterization of the sintered ASS 316L samples



**Characterization**

**Tribological Properties**

Reciprocating Sliding

3 samples
Alumina ball

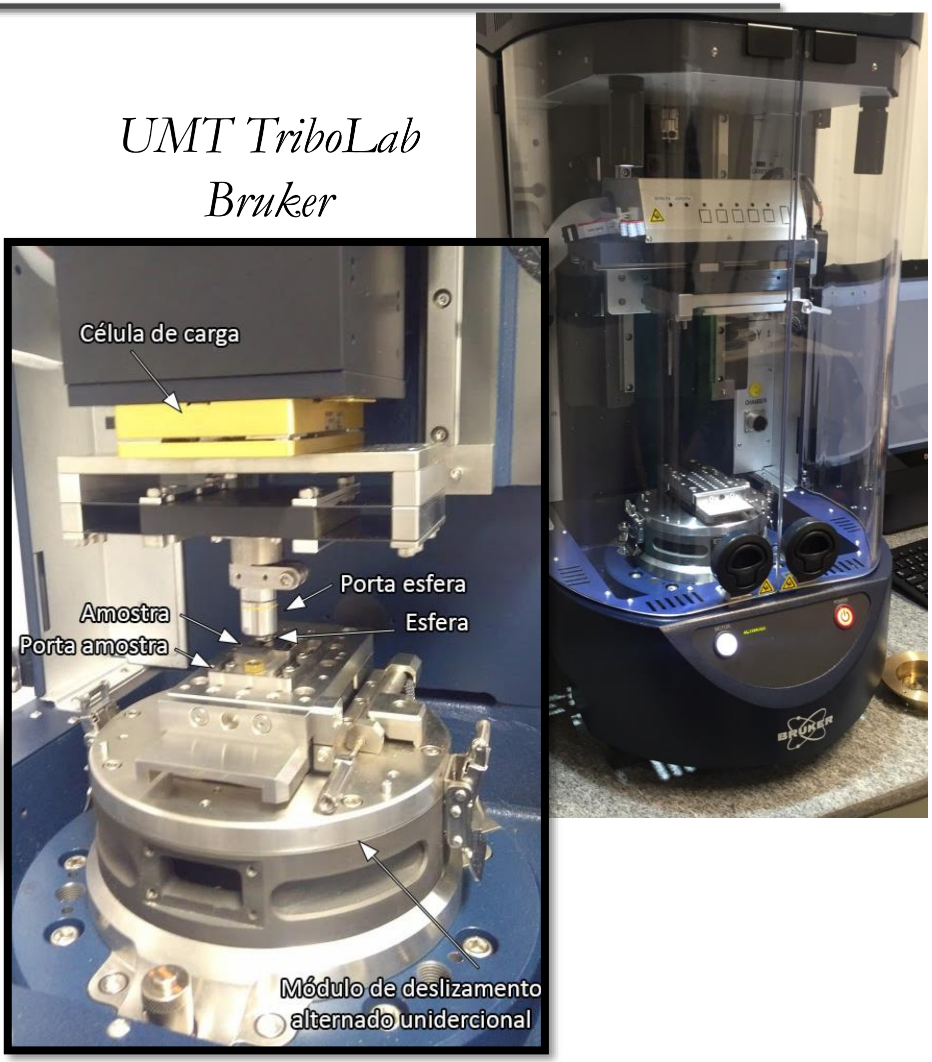
Load 8 N
3 Hz

Time:7200 s
Length:4 mm

Friction
Coefficient

Wear rate
Wear mechanisms

*UMT TriboLab*
*Bruker*



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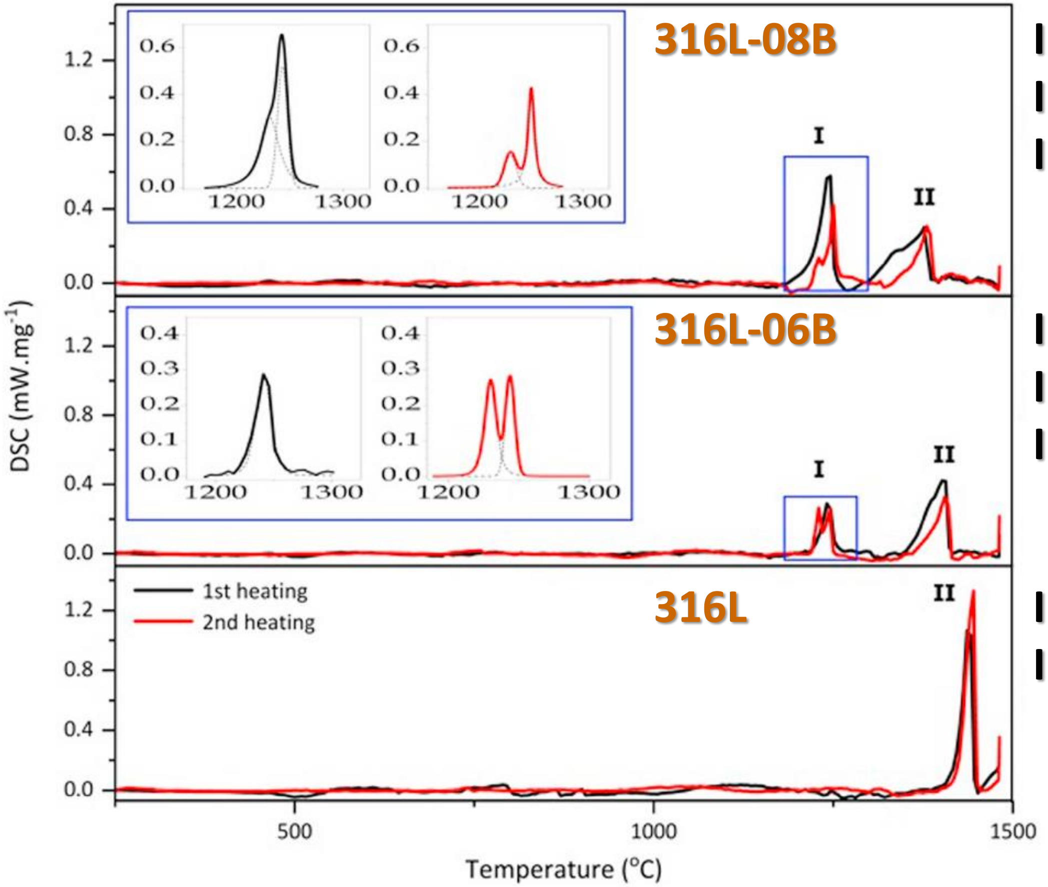
# Thermal analysis



I – Eutectic reaction 1219 °C – 1254 °C
II - Melting onset 1335 °C
II – Complete melting at 1385°°C

I – Eutectic reaction 1223 °C - 1251 °C
II – Melting onset at 1351 °C
II – Complete melting at 1412 °C

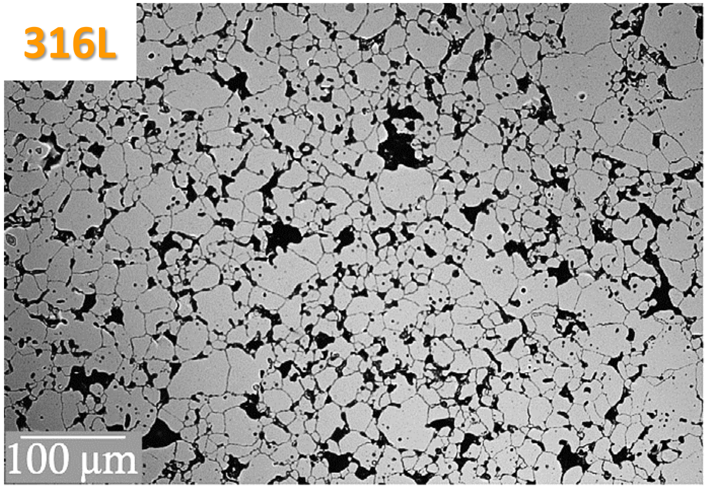
II – Melting onset at 1419 °C
II - Complete melting at 1451 °C

*Serafini, F.L. et al. (2019)*
*Materials Characterization, 152, pp. 253-264.*

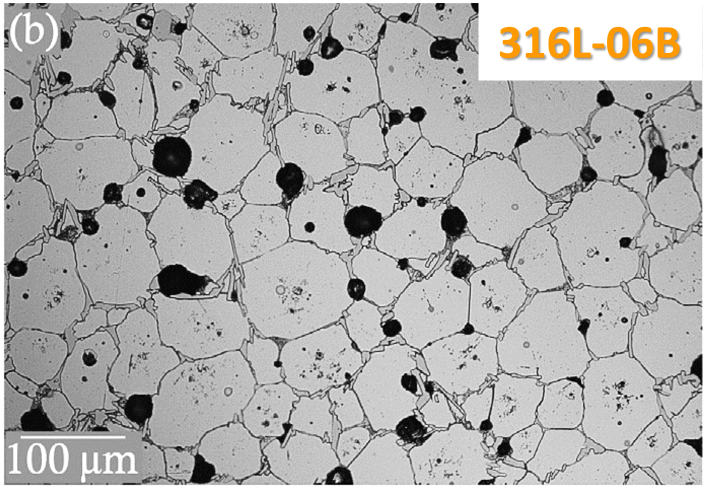
**Boron addition provides**
- ❖ **decrease in liquid phase temperature**
- ❖ **greater amount of liquid phase**

# Microstructure

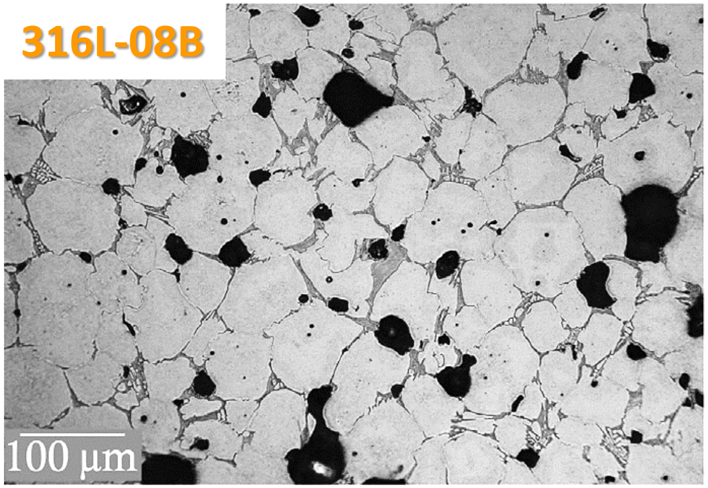
**316L**



**316L-06B**



**316L-08B**

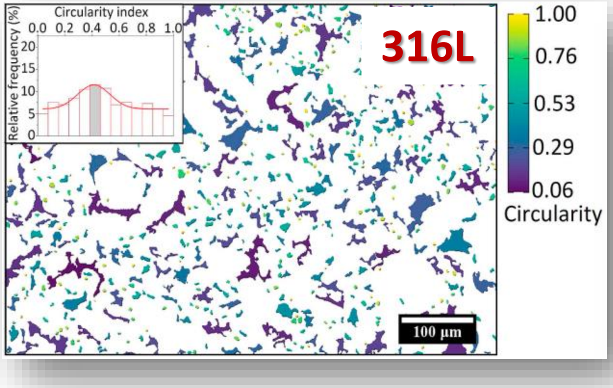


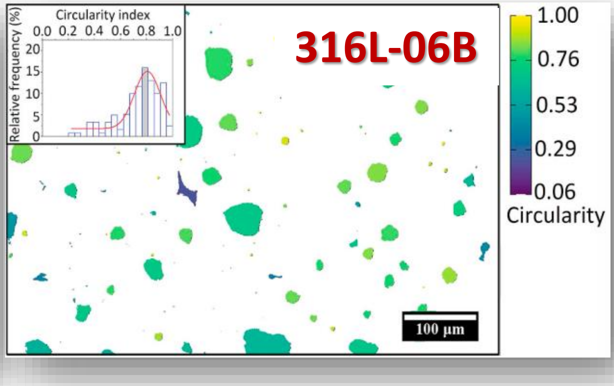
**Microstructure of the B-free and B-containing sintered samples**

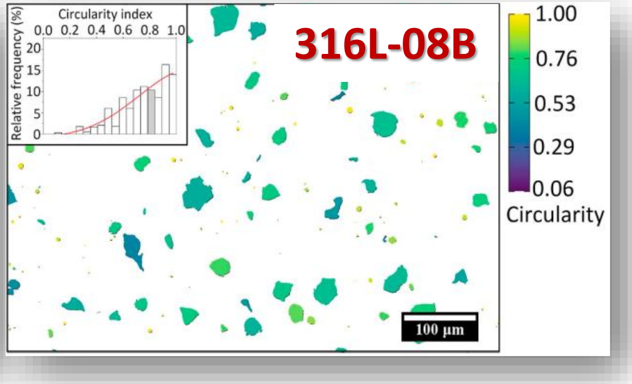
- **Porosity**
- **Austenitic grains**
- **Phases at the grain boundaries**

*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

# Porosity analysis





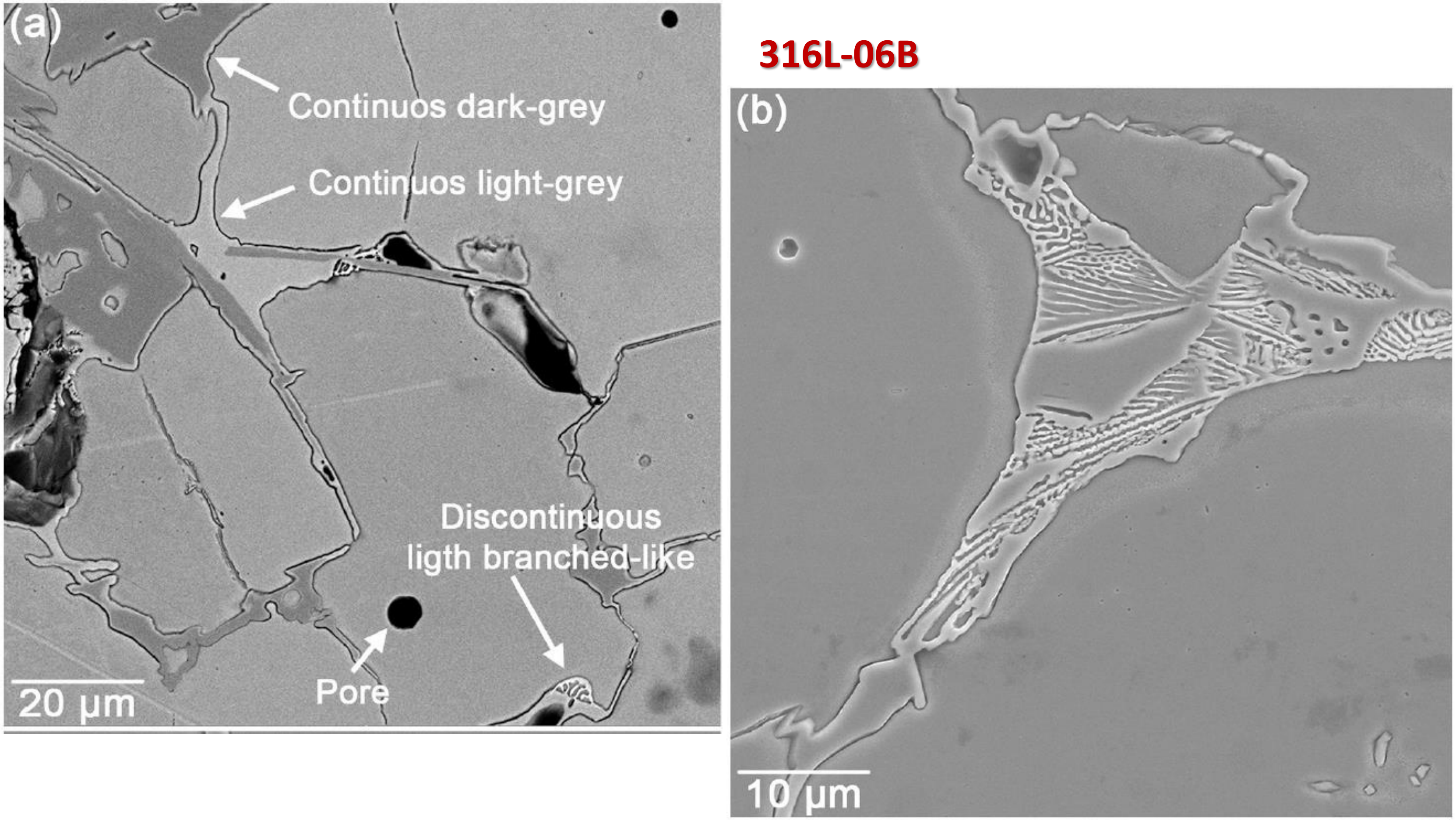


| Sample | Porosity (%) | Pore size, $D_{90}$ (µm) | Circularity index, $C_I$ |
|---|---|---|---|
| 316L | 12.89 | 14.51 | 0.4 |
| 316L-06B | 5.66 | 20.51 | 0.8 |
| 316-08B | 7.7 | 26.17 | 0.8 |

- **Irregular and interconnected pores were formed for the boron-free sample**
- **Nearly circular and isolated pores were developed in the boron-containing samples**

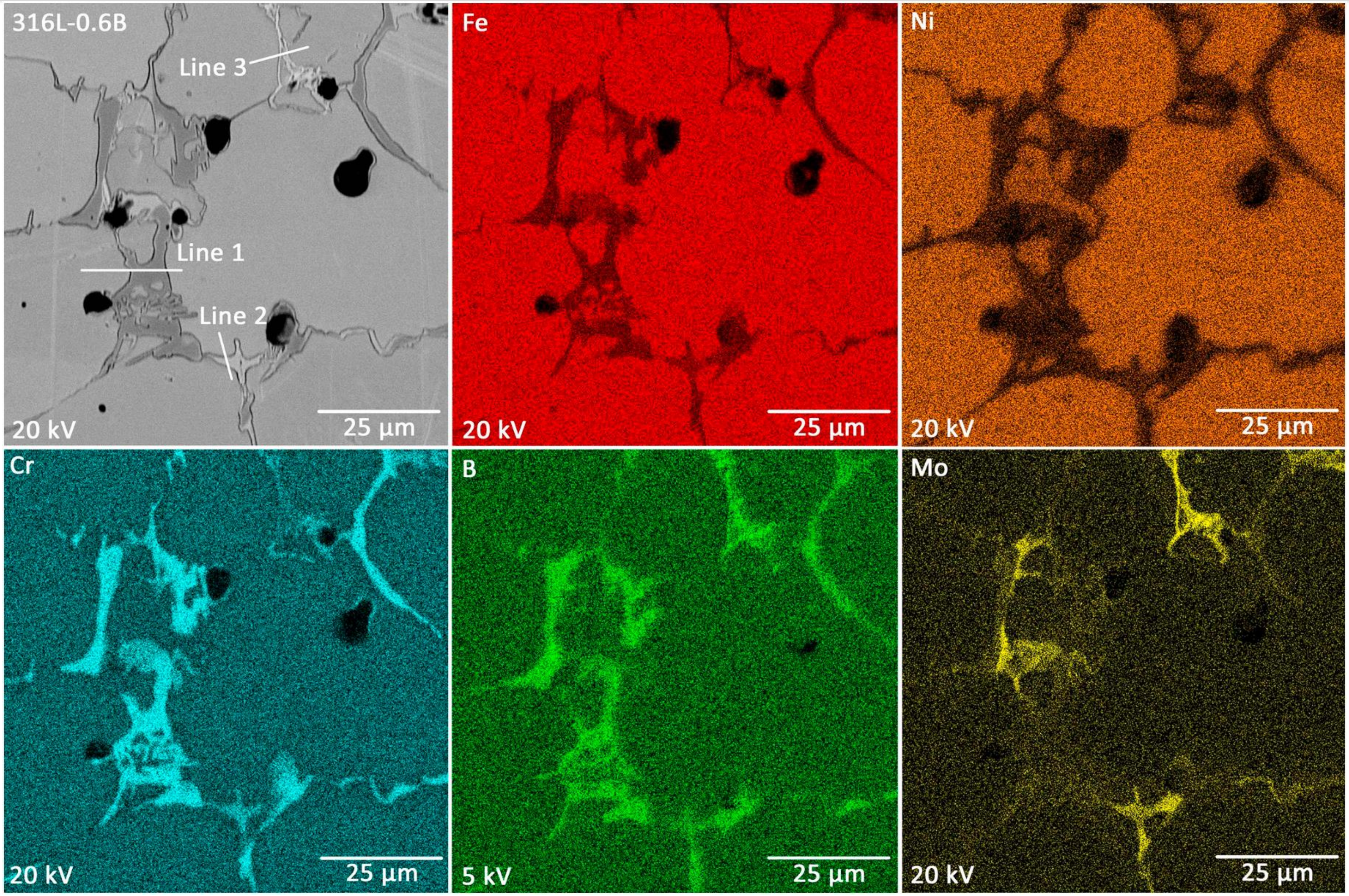
*Serafini, F.L. et al. (2019) Materials Characterization, 152, pp. 253-264.*

# Microstructure



*Serafini, F.L. et al. (2019) Materials Characterization, 152, pp. 253-264.*

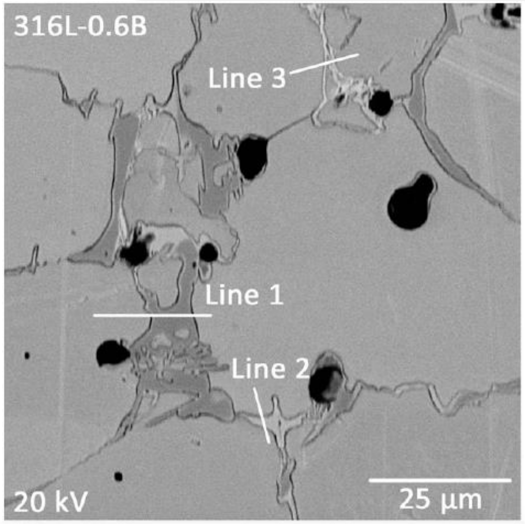
# Microstructure – EDS mapping



*Serafini, F.L. et al. (2019) Materials Characterization, 152, pp. 253-264.*

# Microstructure – EDS line

*Serafini, F.L. et al. (2019) Materials Characterization, 152, pp. 253-264.*



**Line 1 – Continuous dark-grey phase, Cr-rich boride**

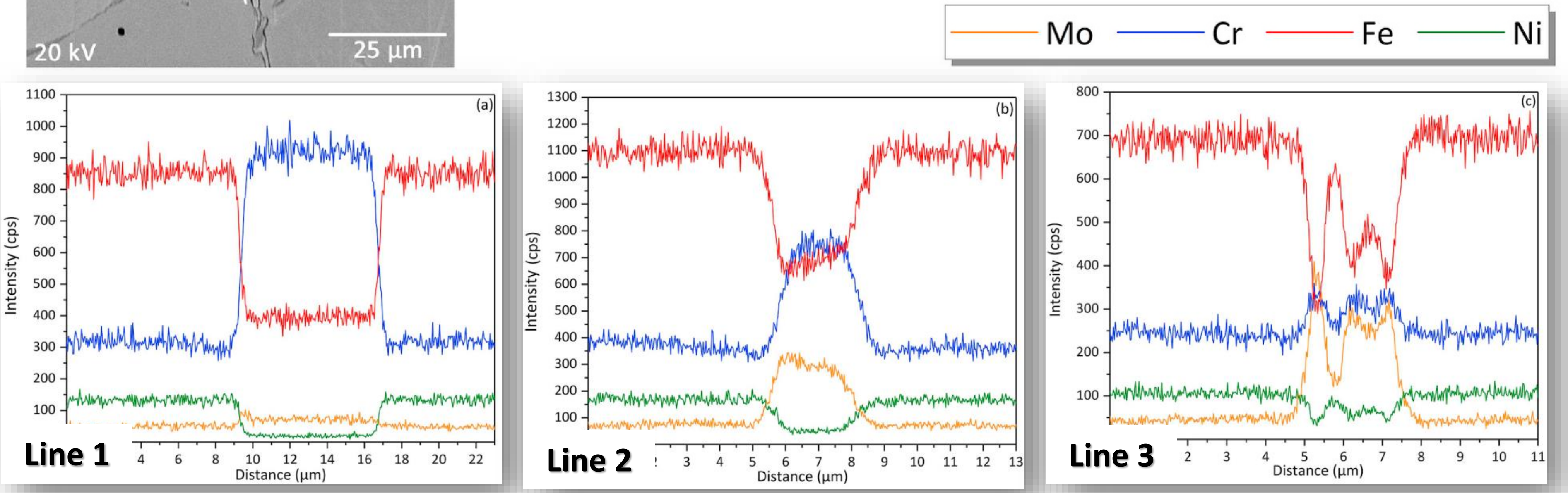
Orthorhombic, $Fe_{1.1}Cr_{0.9}B_{0.9}$

**Line 2 – Continuous light-gray phase, Cr- and Mo-rich boride**

Cubic, $Cr_{23}(B_{1.5}C_{4.5})$

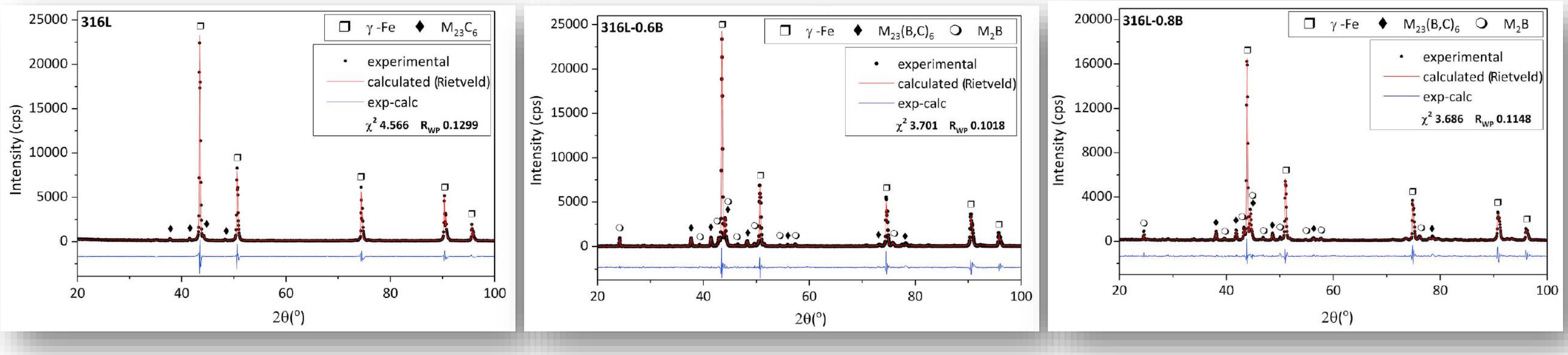
**Line 3 – Discontinuous phase, Mo-rich boride**

Tetragonal, $Cr_{1.75}Mo_{0.25}B$



# Crystalline phases

| Sample | γ-Fe | $M_{23}C_6$ | $M_{23}(B,C)_6$ | $Fe_{1.1}Cr_{0.9}B_{0.9}$ | $Cr_{1.75}Mo_{0.25}B$ |
|---|---|---|---|---|---|
| | Cubic | Cubic | Cubic | Orthorhombic | Tetragonal |
| **316L** | 95.47% | 4.53% | | | |
| **316L-0.6B** | 78.27% | | 6.39% | 9.40% | 5.94% |
| **316L-0.8B** | 66.21% | | 15.46% | 9.40% | 7.91% |



*Serafini, F.L. et al. (2019) Materials Characterization, 152, pp. 253-264.*

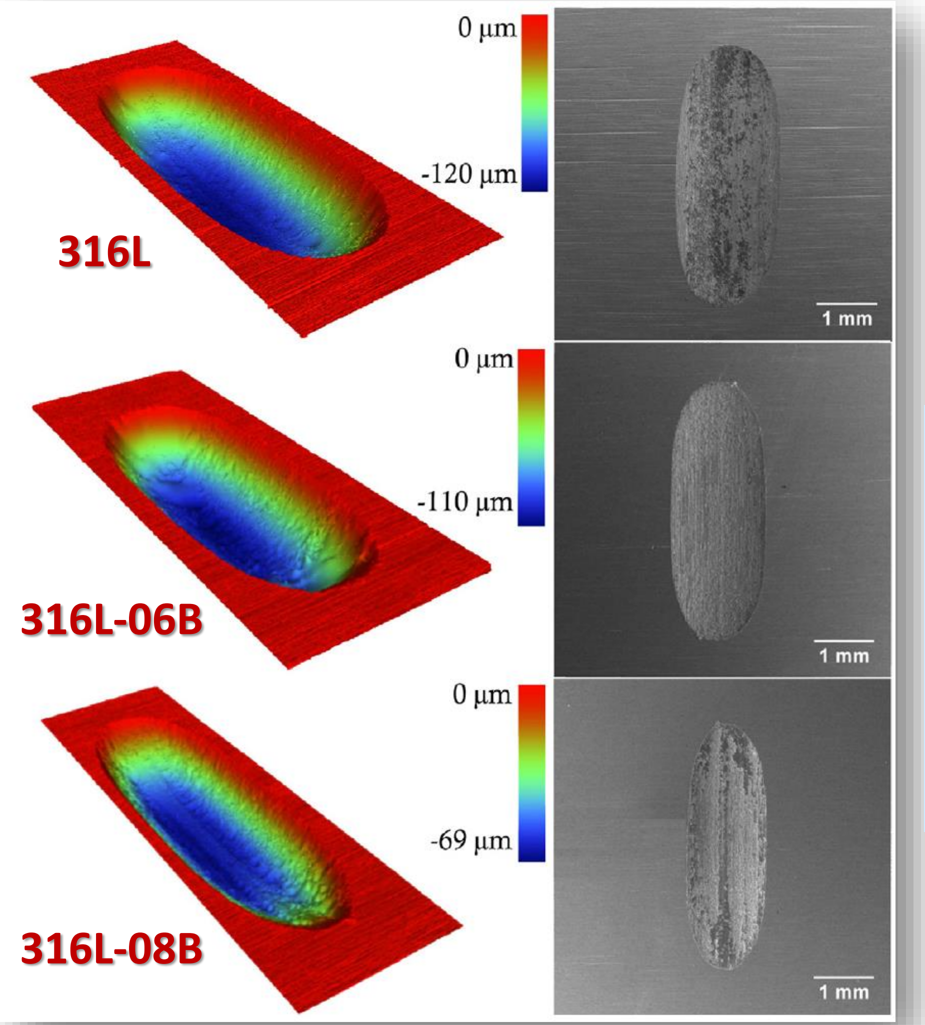
# Density and hardness

| Sample | Density ($g/cm^3$) | Vickers Hardenss ($HV_{10}$) | Instrumented indentation hardness (GPa) | | |
|---|---|---|---|---|---|
| | | | Austenite | Dark-grey boride, Cr-rich | Discontinuous boride, Mo-rich |
| **316L** | 7.13 ± 0.04 | 89 ± 3 | 1.6 ± 0.1 | - | - |
| **316L-06B** | 7.37 ± 0.01 | 159 ± 13 | 1.9 ± 0.1 | 20.5 ± 1.3 | 4.3 ± 0.7 |
| **316L-08B** | 7.35 ± 0.01 | 174 ± 7 | 1.9 ± 0.1 | 22.9 ± 2.1 | 5.0 ± 0.8 |

- **Boron increases the hardness austenitic matrix and creates a network of hard borides along the austenitic grain boundaries**

*Serafini, F.L. et al. (2019) Materials Characterization, 152, pp. 253-264.*

# Reciprocating sliding wear

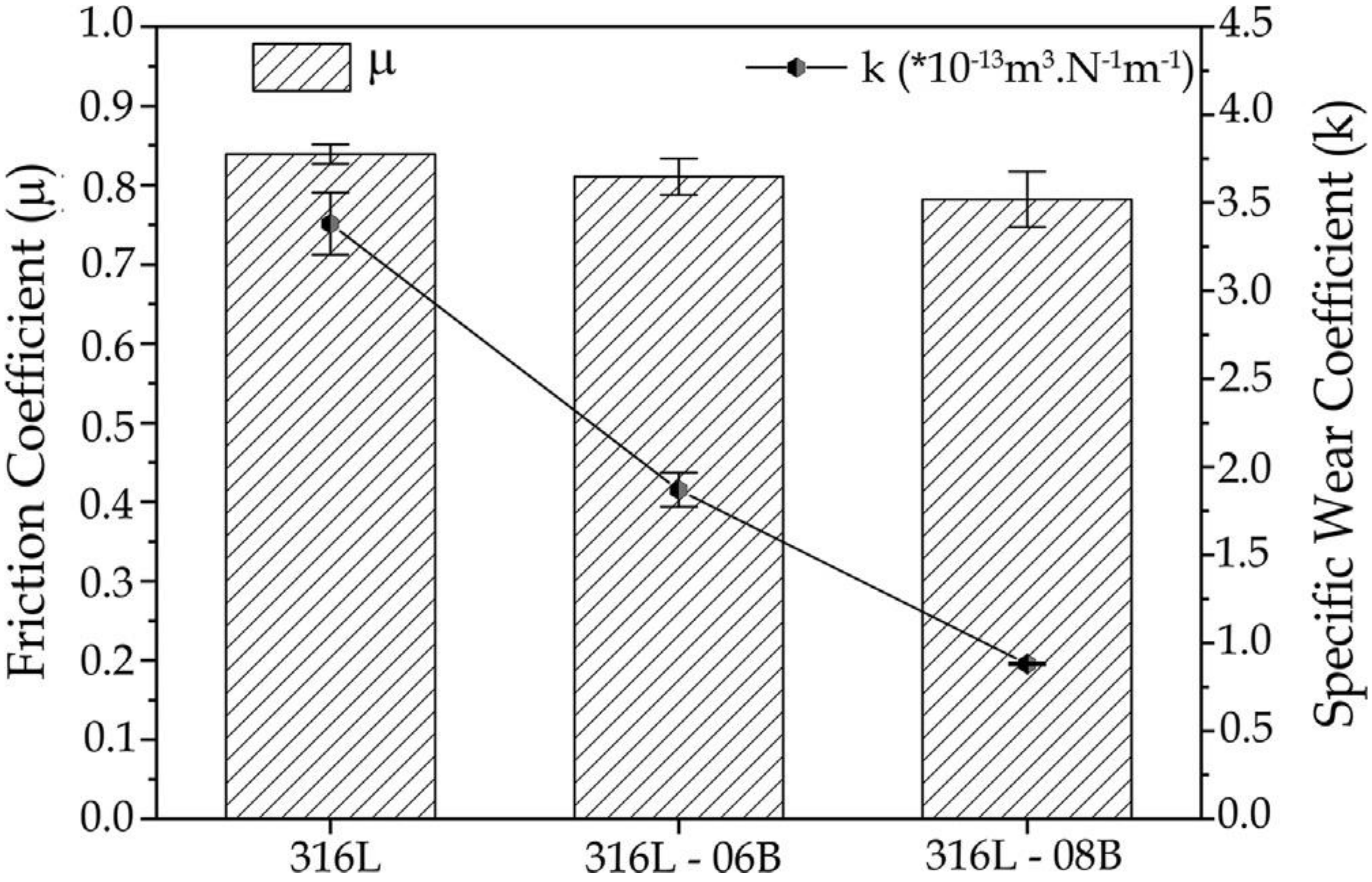


Boron addition

- Narrower and shallower wear tracks
- Improved wear resistance (less material removal) that can be related to
  - Rounded pores (stress concentration regions)
  - Hard borides (less plastic deformation)

*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

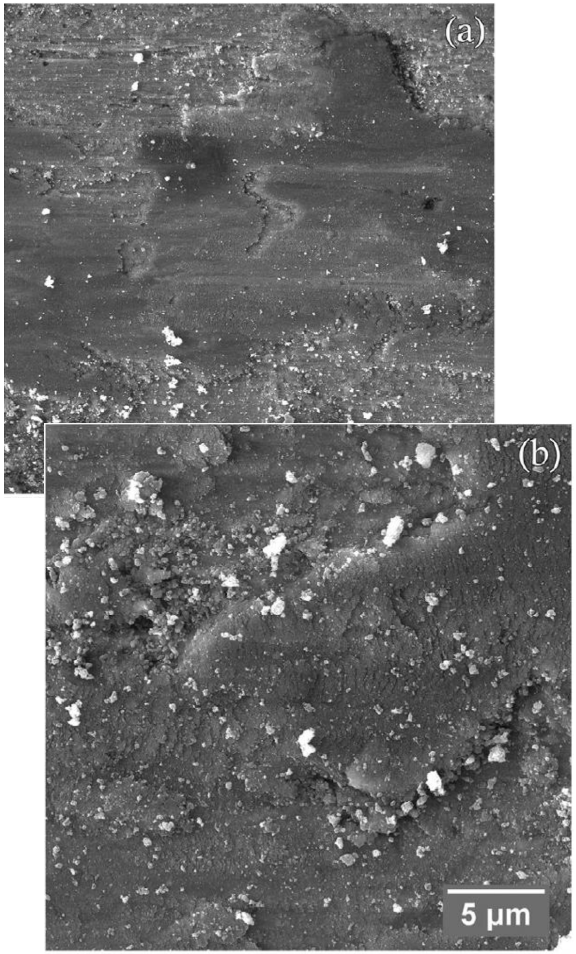
# Friction behavior



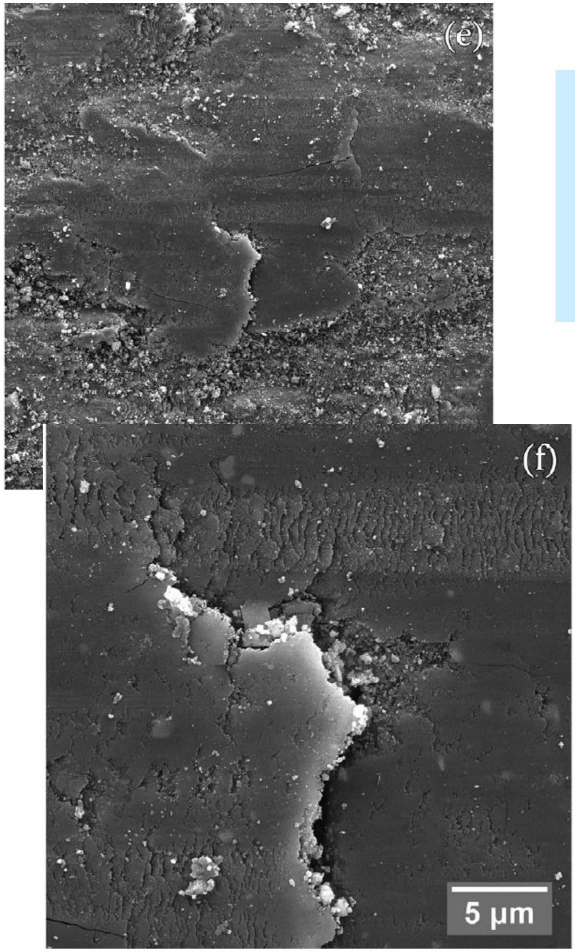
*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

# Worn surfaces

**316L**



**316L-08B**

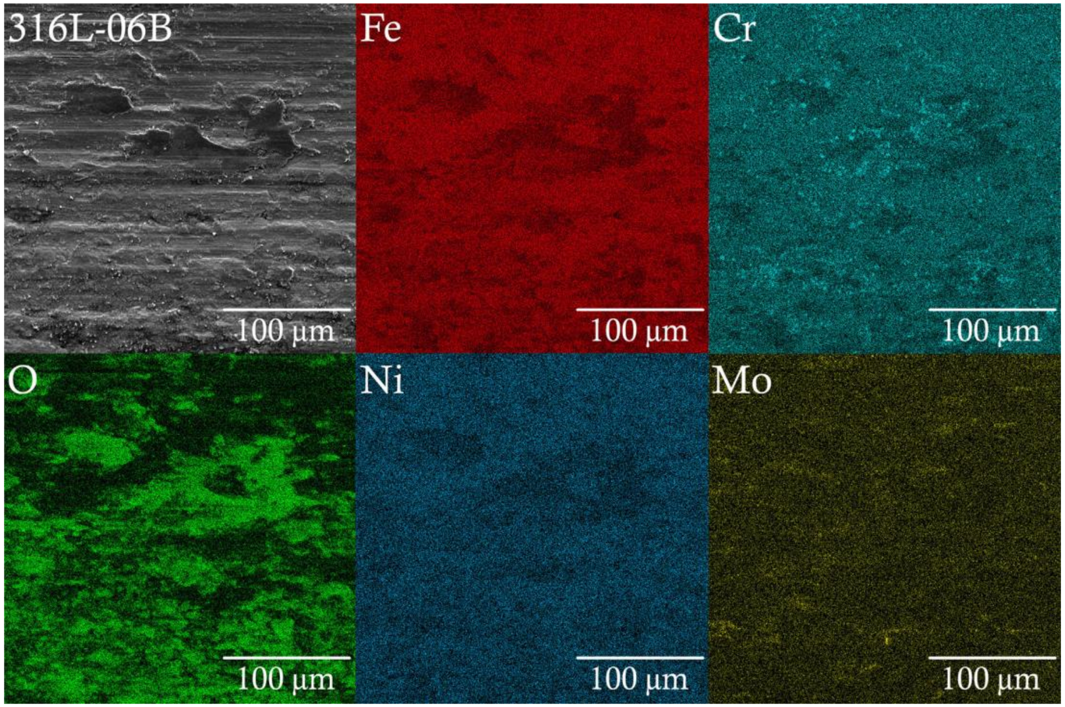


**Adhesive wear**

plastic deformation, material transferring and abrasion grooves

*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

# Worn surfaces



*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

**Adhesive wear**

plastic deformation,

material transferring and abrasion grooves

**Oxidative wear by metallic**

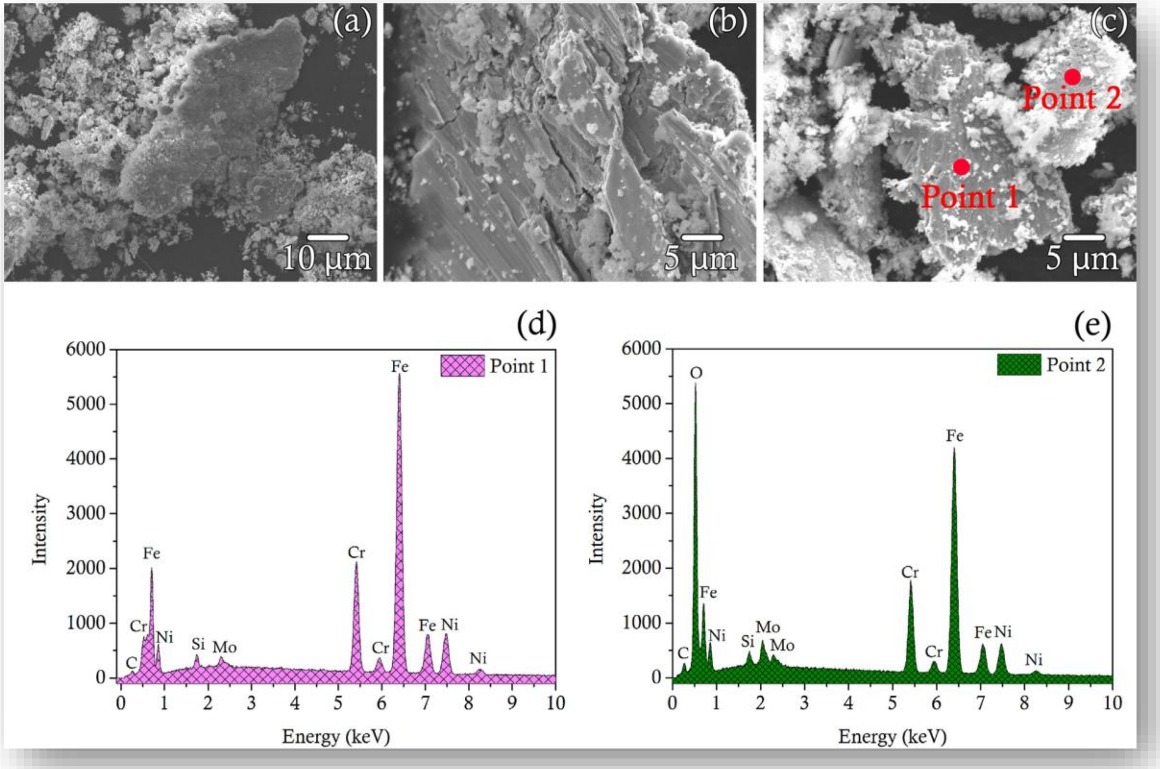
**particle oxidation**

transfer layer is a mixture of oxide and metallic particles) and composed of small clustered particles

*I. Hutchings, P. Shipway, Tribology: Friction and Wear of Engineering Materials, 2017.*
*F.H. Stott, Tribol. Int. 31 (1–3) (1998) 61–71.*

*mcmfarias@ucs.br*

# Wear particles



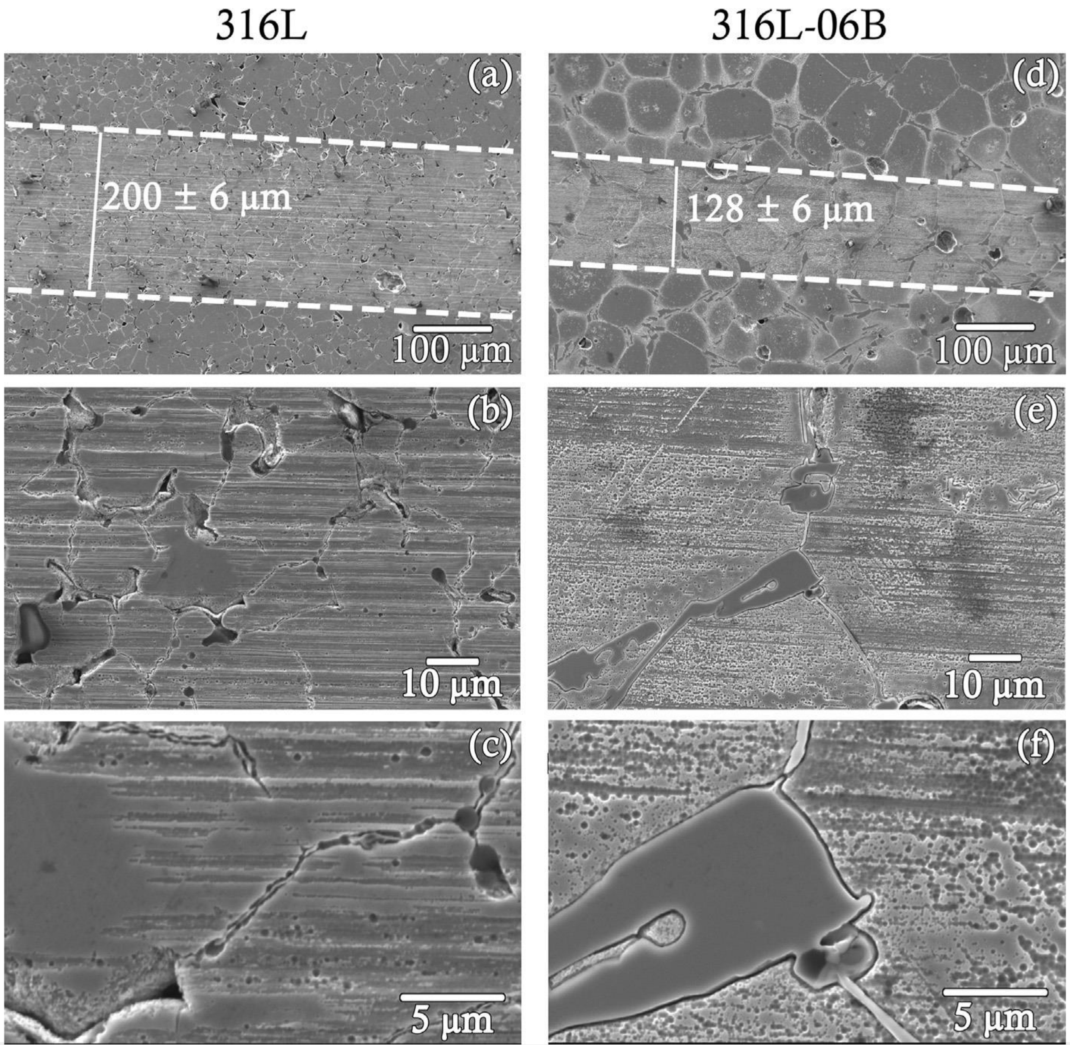
*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

**Wear particles**

plate and lamellar morphologies

same composition of transfer layer

# Single-pass sliding test



**Single-pass sliding test**

Evaluation of load carrying capability of each microstructural constituent (austenite matrix and boron-based precipitates)

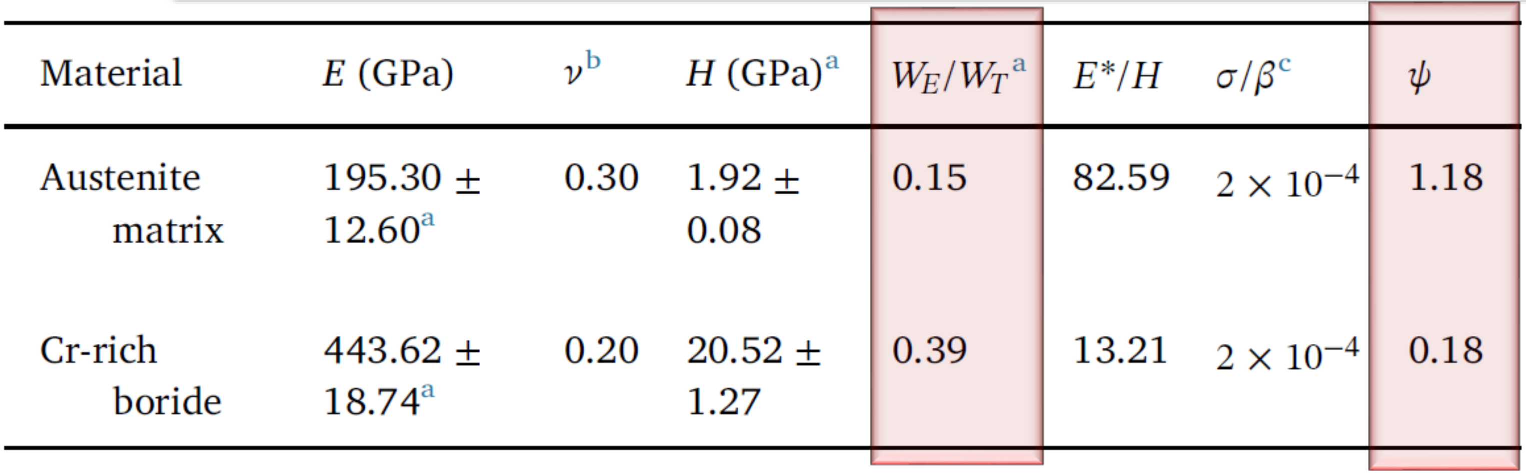
Restrict the formation of wear particles, plastic deformation, strain-induced martensitic transformation or oxidation of surface

- Plastic deformation and abrasion grooves in the austenite matrix
- Borides are free of any damage

*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*

# Single-pass sliding test

*Peruzzo et al. (2019) Wear, 422-423, pp. 108-118.*



| Material | $E$ (GPa) | $\nu$[b] | $H$ (GPa)[a] | $W_E/W_T$[a] | $E^*/H$ | $\sigma/\beta$[c] | $\psi$ |
|---|---|---|---|---|---|---|---|
| Austenite matrix | 195.30 ± 12.60[a] | 0.30 | 1.92 ± 0.08 | 0.15 | 82.59 | $2 \times 10^{-4}$ | 1.18 |
| Cr-rich boride | 443.62 ± 18.74[a] | 0.20 | 20.52 ± 1.27 | 0.39 | 13.21 | $2 \times 10^{-4}$ | 0.18 |

"Plastic contact"
$\psi > 0.6$

"Elastic contact"
$\psi < 0.6$

Plasticity index

$$\psi = \left(\frac{E^*}{H}\right)\left(\frac{\sigma}{\beta}\right)^{1/2}$$

Energy ratio

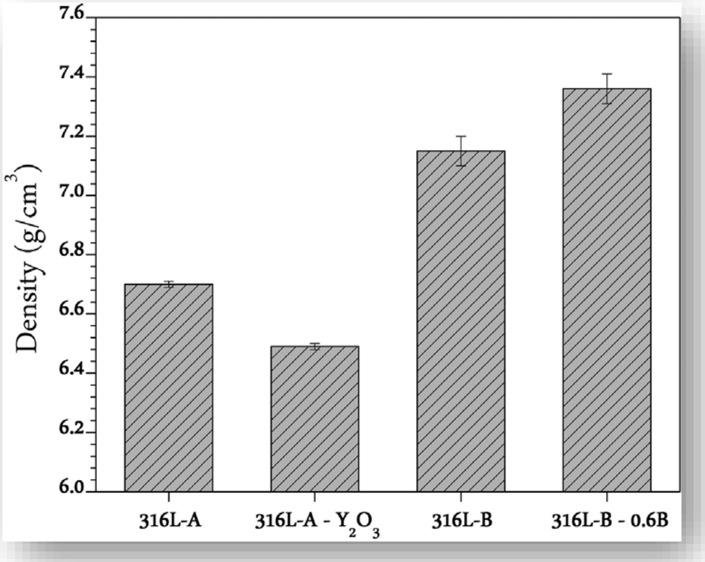
$$\frac{W_E}{W_T} = \lambda \frac{H}{E^*}$$

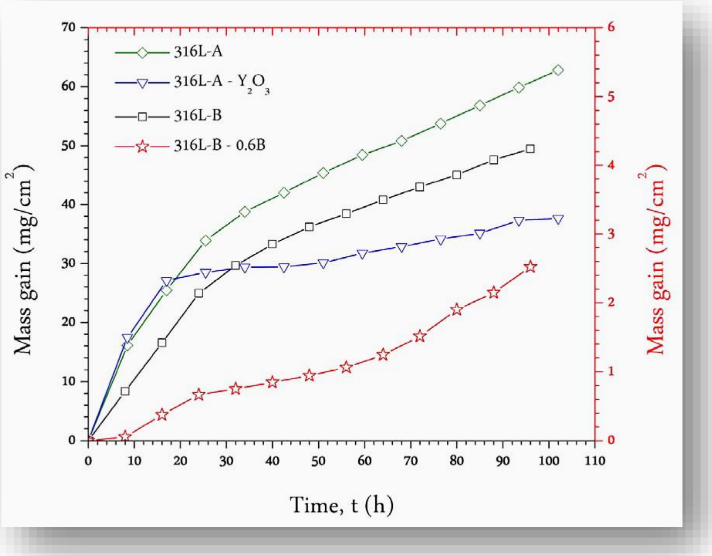
| Material | Dynamic hardness (MPa) | Friction coefficient |
|---|---|---|
| 316L | 510 | 0.22 |
| 316L-06B | 1244 | 0.10 |

**Borides have also load carrying capacity**

*J.A. Greenwood, J.B.P. Williamson, Proc. R. Soc. A: Math. Phys. Eng. Sci. 295 (1442) (1966) 300–319.*

# High-temperature cyclic oxidation at 900ºC

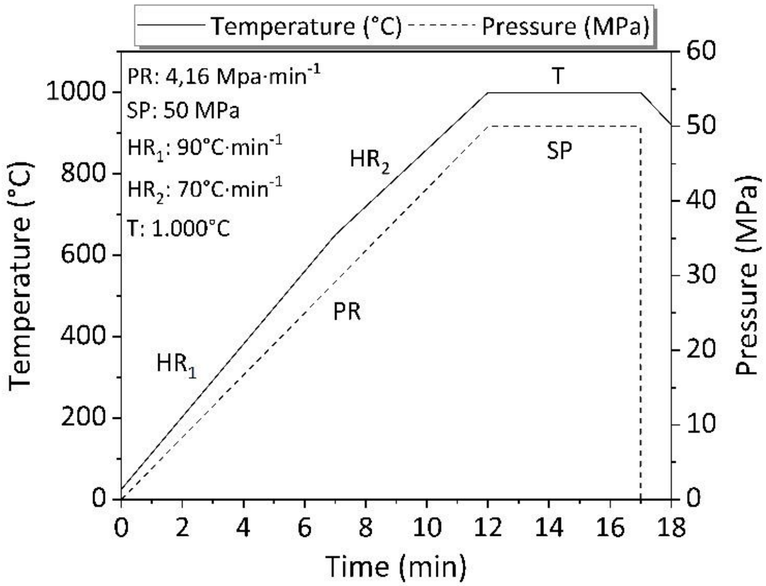


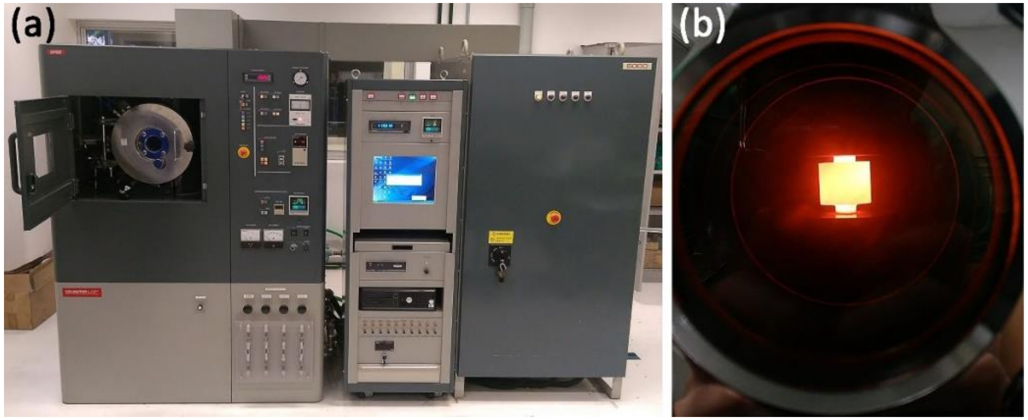


- ❖ Boron to the 316L steel **strongly improves the cyclic oxidation resistance**
- ❖ **Rounded and smaller pores** contribute with the **reduction** in the **porosity** and the active area for oxidation, (this tendency is more pronounced in the boron-containing steel
- ❖ **Yttria** addition **also improves the oxidation resistance** of the steel in a lower ratio than boron

*Peruzzo, M., et al. (2017) Corrosion Science, 129, pp. 26-37.*

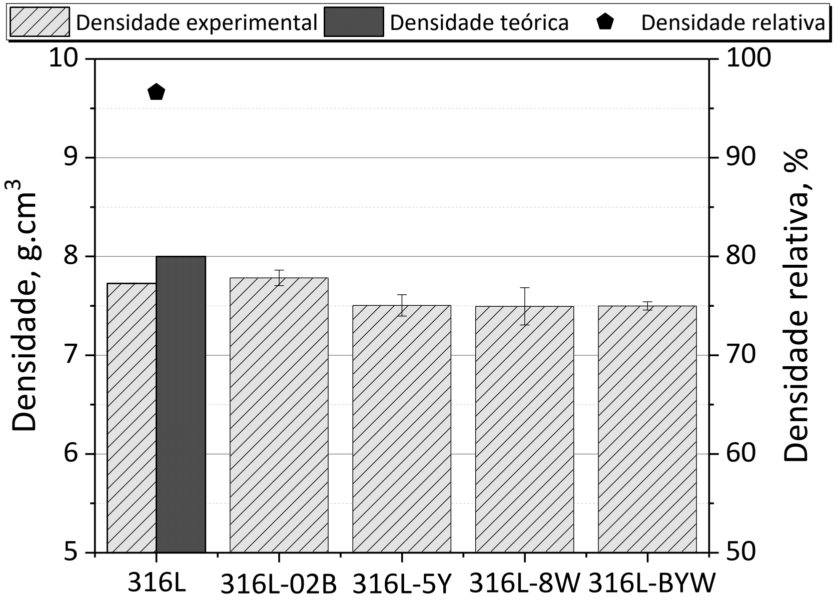
# ASS obtained by SPS – recent results

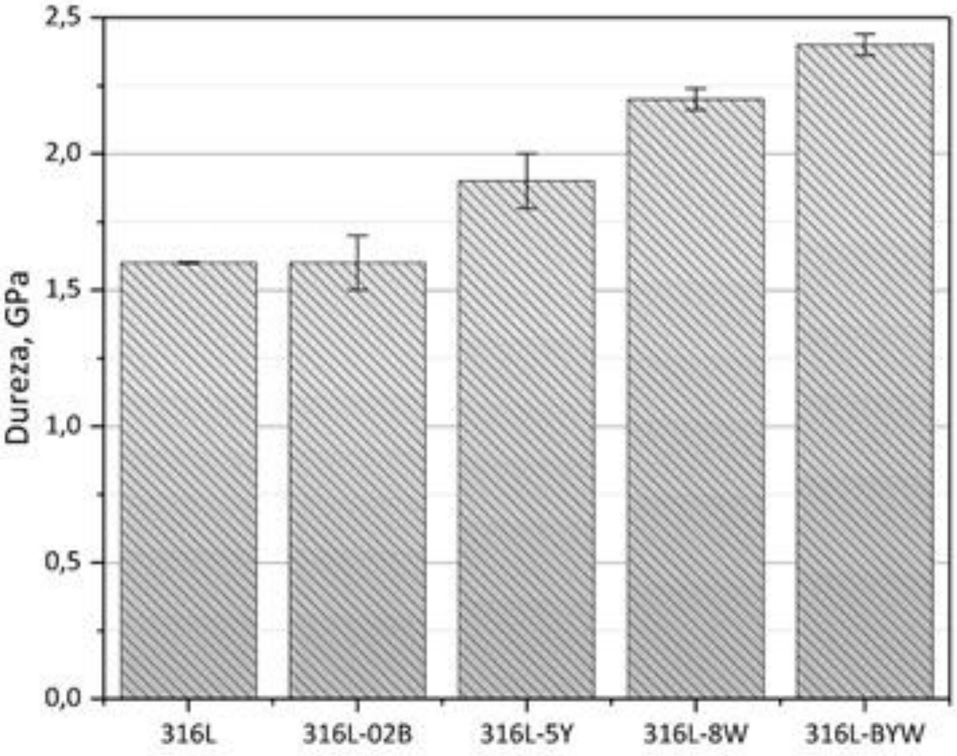




*Serafini, F.L. et al. (to be published).*

# ASS obtained by SPS – recent results



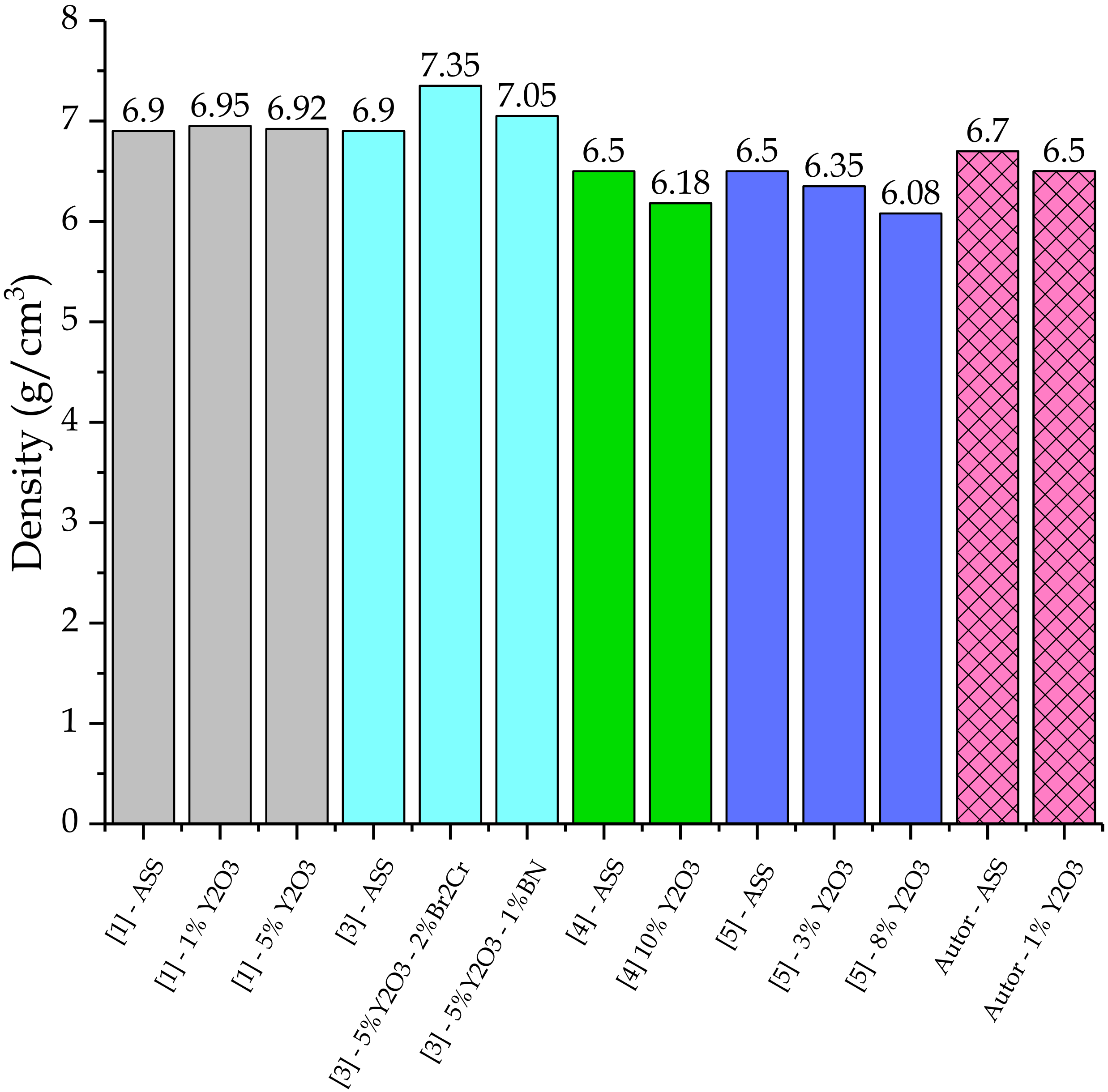


*Serafini, F.L. et al. (to be published).*

| | Base material | Additive type | Additive amount (wt%) | Density (g/cm$^3$) | Hardness | k mm$^3$/Nm | Sintering parameters |
|---|---|---|---|---|---|---|---|
| [1] | 6.90 g/cm$^3$<br>110 HV5 | $Y_2O_3$ | 1 – 5 | 6.95 – 6.92 | 127 – 155 | … | 1300 ºC, 1 h, Hydrogen |
| [2] | 6.90 g/cm$^3$<br>110 HV5 | $Y_2O_3$<br>Cu<br>Cu-Sn<br>$Fe_3P$<br>Si | 3<br>1 – 3<br>1 – 3<br>1 – 2<br>1 – 5 | … | 122<br>104 – 100<br>135 – 127<br>171 – 218<br>85 – 80 | … | 1300 ºC, 1 h, Hydrogen |
| [3] | 6.90 g/cm$^3$<br>38 HRB<br>6.1x 10$^{-13}$ mm$^3$/Nm | $Y_2O_3$-$B_2Cr$<br>$Y_2O_3$-BN | 5-2<br>5-1 | 7.35<br>7.05 | 74<br>63 | 3.5x 10$^{-13}$<br>4.7x 10$^{-13}$ | 1250 ºC, 30 min, Vacuum |
| [4] | 6.5 g/cm$^3$ | $Y_2O_3$ | 10 | 6.18 | … | … | 1250 ºC, 60 min, Hydrogen |
| [5] | 6.61 g/cm$^3$<br>82 HV5 | $Y_2O_3$ | 3 – 8 | 6.35 – 6.08 | 118 – 125 | … | 1350 ºC, 1 h, Hydrogen |

[1] S. Lal, G.S. Upadhyaya. J. Mater. Sci. 24 (9) (1989) 3069–3075.
[2] S. Lal, G.S. Upadhyaya. Sol. Sta. Phen. 8-9 (1990) 361–368.
[3] M. Vardavoulias, et al. Tribol. Int. 29 (6) (1996) 499–506.
[4] J. Shankar, et al. Corros. Sci. 46 (2004) 487–498.
[5] A. Raja Annamalai et al. Corros. Eng. Sci. Technol. 50 (2015) 91–102.

# Data compilation Properties of P/M ASS



**Data compilation**

**Effect of additives in density of P/M ASS**

**Sintered Austenitic Stainless Steel**

# Final remarks

- Boron can be used either **elemental** or in **compound** (FeB, $Fe_2B$, NiB and $Cr_2B$) as an additive in iron-based systems and stainless steels
- Boron acts as a **sintering enhancer**, and sintering **temperature** can be **reduced** to about 1240 °C
- The addition of **boron in elemental** form results in the **good properties** and structure for stainless steel
- Boron addition **up to 0.8 wt%** for 316L stainless steel powders **increases density, mechanical properties, corrosion, and wear resistance**. Nearly full densification was obtained with enough eutectic phase formation
- Yttria addition improves high-temperature oxidation of P/M ASS.
- *The resultant parts might be used in applications where wear and high-temperature resistance are desired*

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- Profa. Dra. Isabel Fernanda Machado
- Prof. Dr. Amilton Sinatora
- Prof. Dr. Roberto Martins de Souza

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