Topology Optimization of Tribological Composites for Multifunctional Performance at Sliding Interfaces

7th TOP Webinar
2020-11-24

Natasha Vermaak

BASED ON: Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

Dr. Xiu JIA
xjia005@sina.com

LEHIGH
UNIVERSITY

vermaak@lehigh.edu

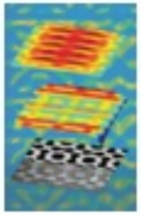
In The Vermaak Lab

Science
is real

Love
is love

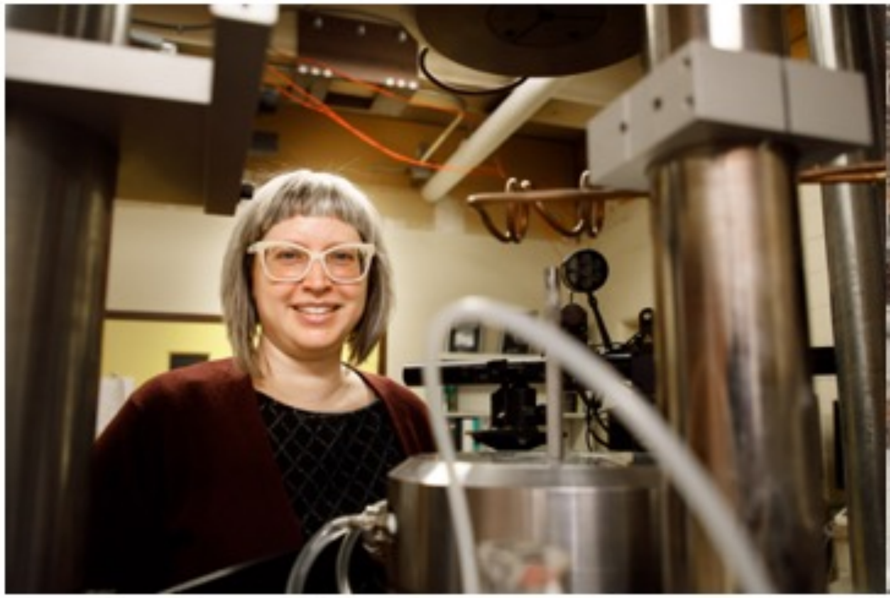
Black lives
matter

Feminism
is for everyone



Materials
Design is cool

Immigrants
are welcome



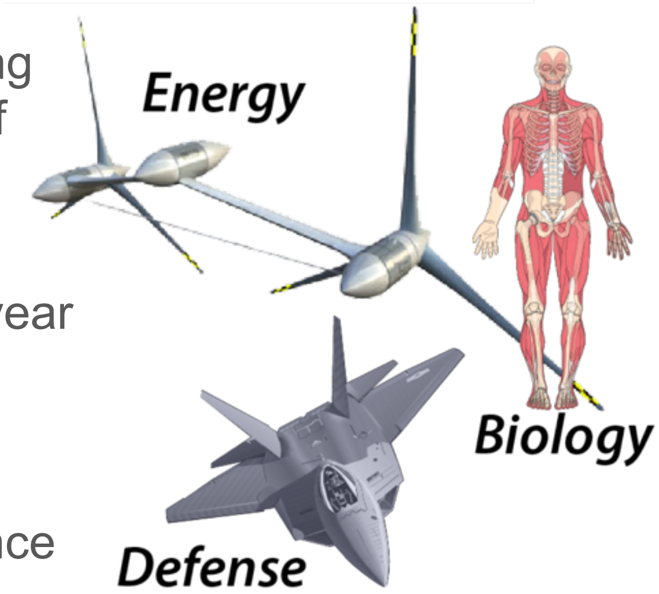
Adapted from @SammyKatta: www.sammykatta.com/diversity

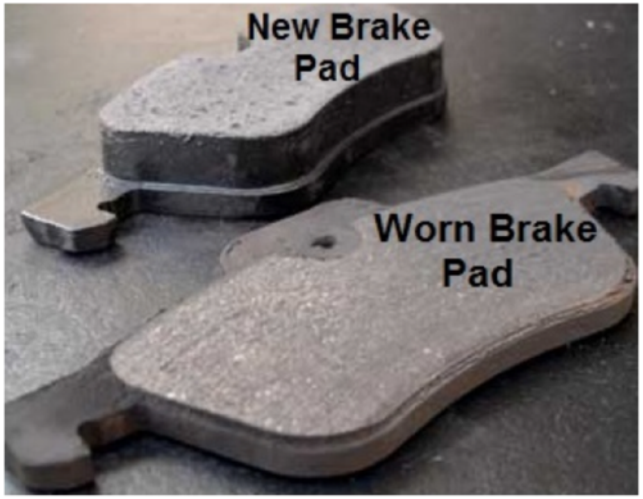
Composites are widely used in tribological applications

What? Tribology is science/engineering of interacting surfaces in relative motion – the principles of friction, wear and lubrication.

Why?

- Cost of friction and wear ~$500B to $1T/year
- Of world's energy consumption, ~23% originates from tribological contacts
- Environmental impacts costly
- Friction and wear are critical to performance of many mechanical systems





Tribological composites

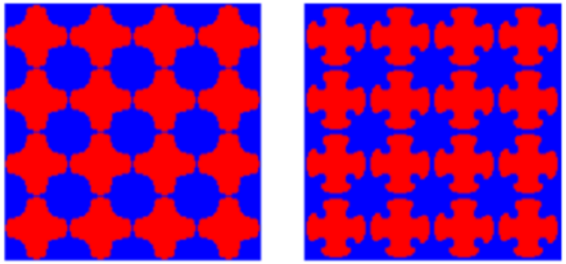
- Improve friction and wear resistance
- Improve mechanical, electrical, optical, electronic, chemical, and magnetic properties
- Metal/metal, metal/ceramic, metal/polymer, polymer/polymer

K. Holmberg, A. Erdemir. "Influence of tribology on global energy consumption, costs and emissions." Friction 5.3 (2017): 263-284.
K. Friedrich, "Polymer composites for tribological applications." Advanced Industrial and Engineering Polymer Research (2018).

Introduce TO for tribological applications

Topology optimization has been widely used to design composites for many multifunctional applications

de Kruijf 2007



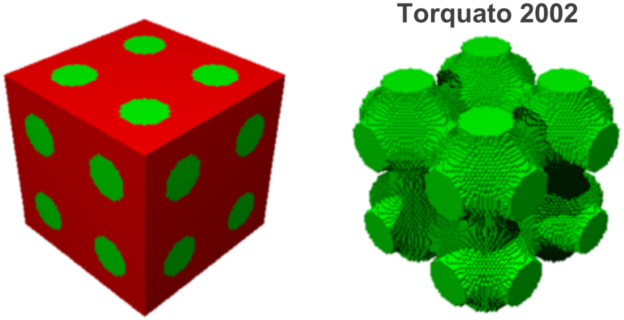
Bulk modulus & thermal conductivity

Amlashi 2020

Mechanical & piezoelectric

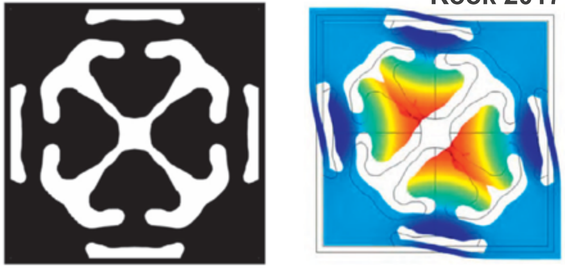
Tribological performance

Torquato 2002



Electrical and thermal conductivities

Kook 2017

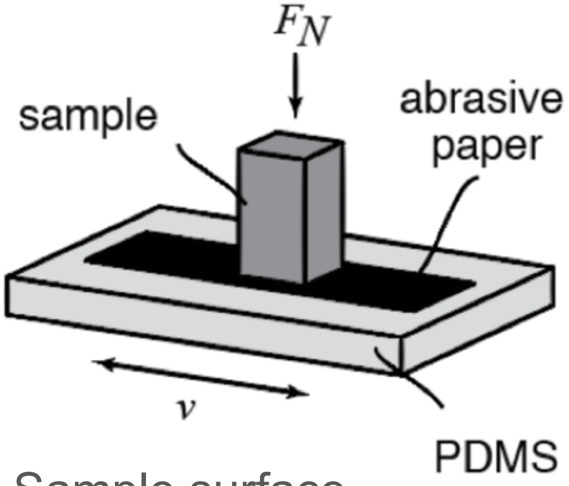


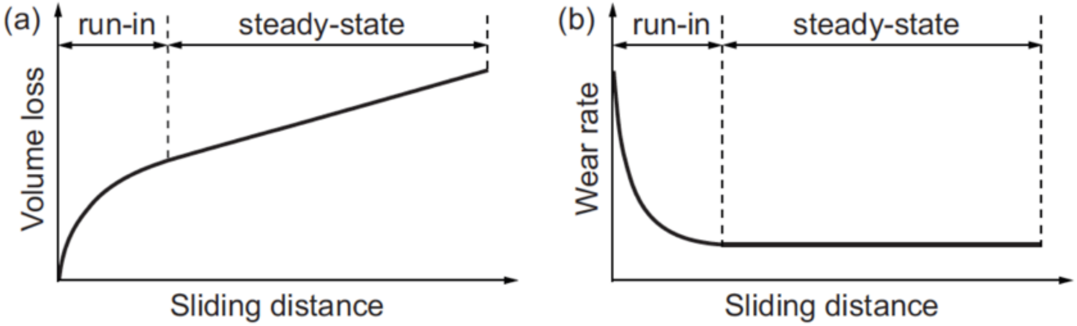
Elastic and acoustic properties

F. Feppon, et al, Introducing a level-set based shape optimization method for the wear of composite materials, SAMO, 55 (2) pp. 547-568, (2017).
N. de Kruijf, et al. "Topological design of structures and composite materials with multiobjectives." Int. J. Sol. & Struct. 44, no. 22-23 (2007): 7092-7109.
S. Torquato, et al. "Multifunctional composites: optimizing microstructures for simultaneous transport of heat and electricity." PRL 89, no. 26 (2002): 266601.
J. Kook, et al. "Topology optimization of periodic microstructures for enhanced loss factor using acoustic–structure interaction." Int. J. Sol. & Struct. 122 (2017): 59-68.
A. Homayouni-Amlashi, et al. "2D topology optimization MATLAB codes for piezoelectric actuators and energy harvesters." SAMO (2020): 1-32.

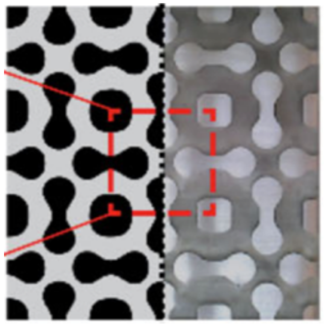
The physical process of **wear**

Linear wear





Sample surface
[48 mm x 48 mm]

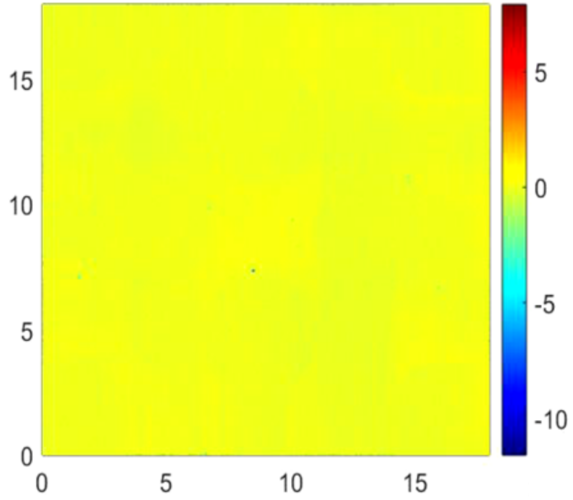


■ Aluminum

□ Epoxy

Composite surface
[16 mm x 16 mm]

Measured Surface
Profile [mm x mm]
Relative height in μm



Grejtak et al. Adv. Eng. Matr. 2019

The physical process of **wear**

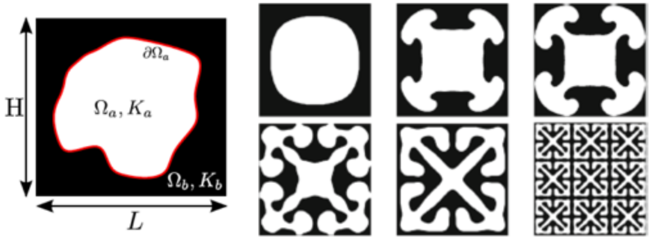
Friction also always occurs during wear

- Temperature rise in sliding components
- Overheating might lead to severe wear, interface degradation & thermally-induced failure

Opportunity for Design:

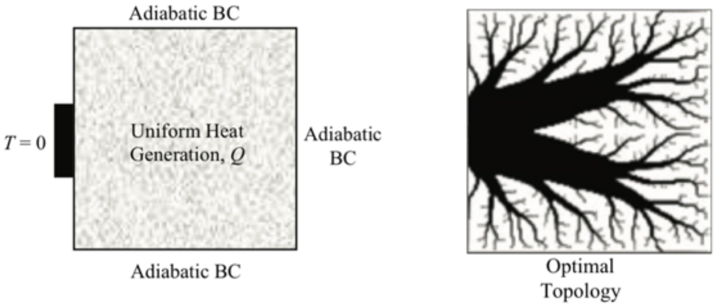
Maximize frictional heat dissipation during wear

Topology optimization for wear



Grejtak, *Adv. Eng. Materials* (2019)
Feppon, *Struct. & Mult. Opt*. (2017)

Topology optimization for heat dissipation



Dbouk, *App. Therm. Eng.* (2017)
Gersborg-Hansen, *Struct. & Mult. Opt*. (2006)
And many more…

Maximize dissipation of frictional heat generated at sliding interface of a bi-material composite during wear while maintaining target steady-state wear performance

Model for wear:

Combines Archard's Law with Pasternak Elastic Foundation

Wear rate: physical coefficient of material's wear resistance (system property)

K

Materials with higher wear rate will wear more

Archard's Law: $\Delta z / \Delta s = PK$

Local surface height (material) loss after a sliding distance is proportional to the material wear rate (K) and the local contact pressure P.

Pasternak model gives pressure distribution: *[Feppon J. Trib. 2016, SAMO 2017]*

Model has been experimentally validated: *[Jia 2017, Jia 2018, Grejtak 2019]*

➡ Prior work showed **steady-state** composite wear rate only depends on constituent material area-fractions at sliding interface

Archard JF, Hirst W (1956) The wear of metals under unlubricated conditions. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 236(1206):397-410

Kerr AD (1964) Elastic and viscoelastic foundation models. Journal of Applied Mechanics 31(3):491

Pasternak PL (1954) On a new method of analysis of an elastic foundation by means of two foundation constants.

F. Feppon, M.S. Sidebottom, G. Michailidis, B.A. Krick, and N. Vermaak, Efficient steady state computation for wear of multimaterial composites, ASME J. of Tribology, 138(3), p.031602 (2016).

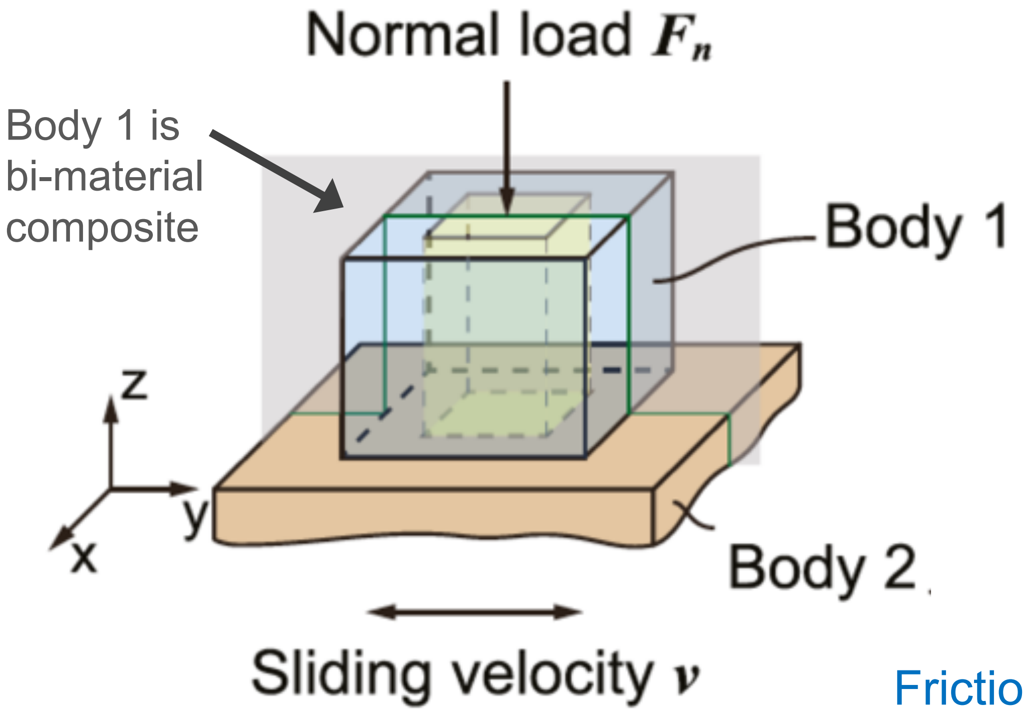
F. Feppon, et al, Introducing a level-set based shape optimization method for the wear of composite materials, SAMO, 55 (2) pp. 547-568, (2017).

X. Jia, et al, Design of composite systems for rotary wear applications, Materials & Design, 134, pp. 281-292, (2017).

X. Jia, et al., Experimentally calibrated abrasive sliding wear model: demonstrations for rotary and linear wear systems. Journal of Applied Mechanics 85(12), pp. 121011-121019 (2018).

X. Jia, et al. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Comp. B: Eng. 199 (2020)

Thermal model for frictional heating:



Body 1 is bi-material composite

$$\nabla \cdot (\boldsymbol{k}\nabla \boldsymbol{T}) = 0, \text{ in } \Omega$$ (Body 1)

BC: $$-\boldsymbol{k}\nabla \boldsymbol{T} \cdot \boldsymbol{n} = \boxed{\dot{q}} \text{ in } \Gamma_{sl}$$ (sliding interface)

Frictional heat flux at the sliding interface is proportional to:

- Sliding velocity
- Coefficient of friction
- Contact pressure

Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

Apply TO (SIMP): thermal opt. + wear constraint

Minimize average temperature rise at sliding interface of a bi-material composite while maintaining target steady-state wear performance

CASE STUDY
1 of 4

***Minimize AVG. temp. rise** at sliding interface*
(initially room temp)

COMPOSITE SYSTEM:

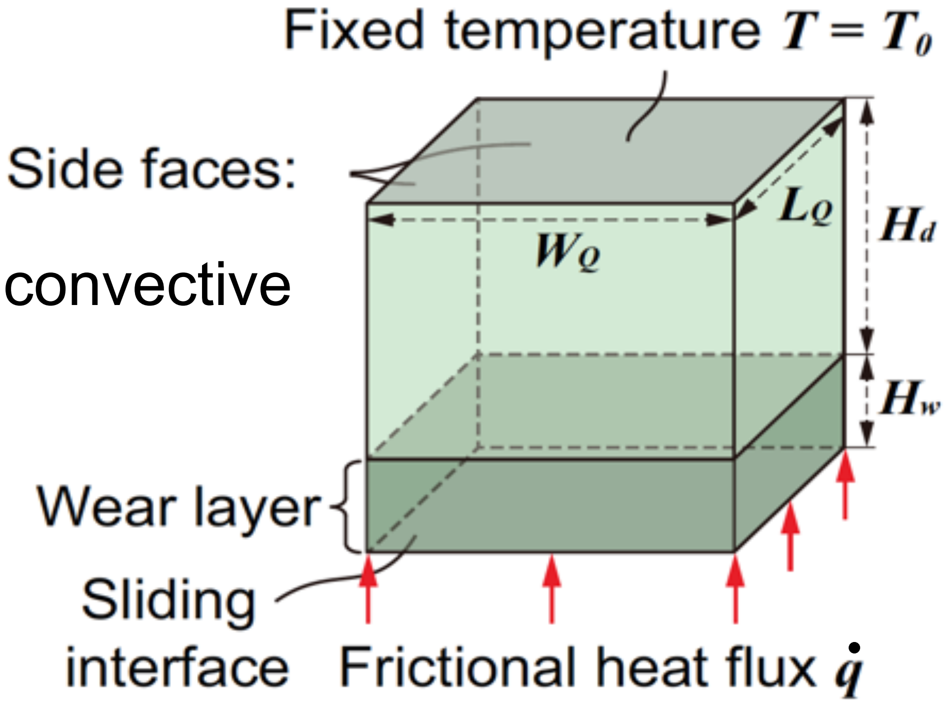
50% metal | 50% ceramic

Metal

- **more conductive**
- **less wear resistant**
- **lower coeff. of friction**
- ➔ **less heat**

Ceramic

- **less conductive**
- **more wear resistant**
- **higher coeff. of friction**
- ➔ **more heat**



Dolata, A.J., 2017. Tribological properties of AlSi12-Al2O3 interpenetrating composite layers in comparison with unreinforced matrix alloy. *Materials*, *10*(9), p.1045.
https://www.ceramtec.com/ceramic-materials/metal-matrix-composites/
K. Friedrich, "Polymer composites for tribological applications." Advanced Industrial and Engineering Polymer Research (2018).
Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

Apply TO (SIMP): thermal opt. + wear constraint

Minimize average temperature rise at sliding interface of a bi-material composite while maintaining target steady-state wear performance

CASE STUDY
1 of 4

***Minimize AVG. temp. rise** at sliding interface (initially room temp)*

COMPOSITE SYSTEM:

50% metal | 50% ceramic

Metal

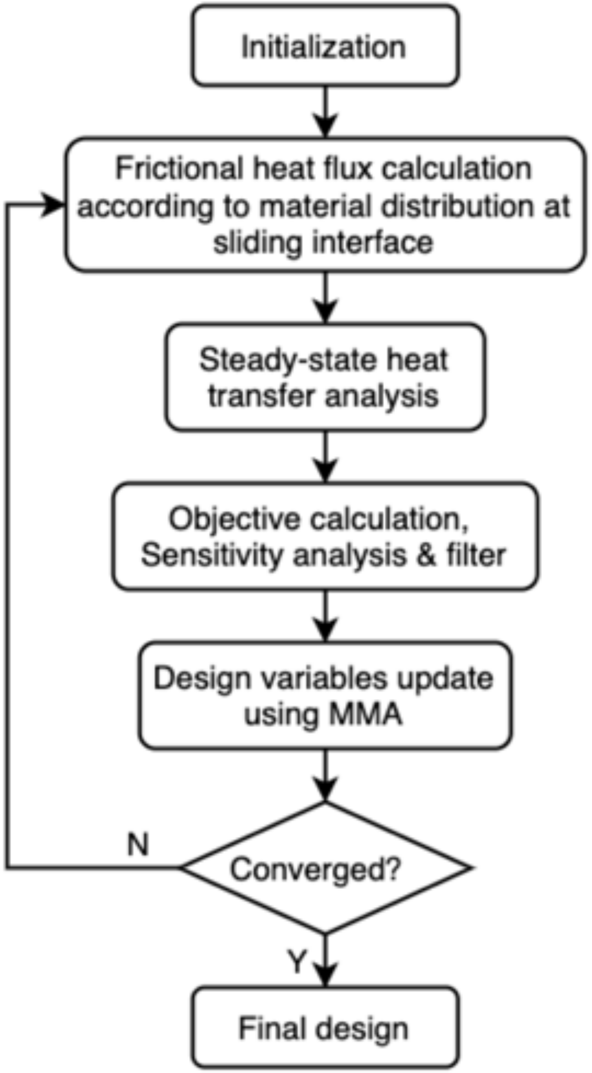
- **more conductive**
- **less wear resistant**
- **lower coeff. of friction**

➔ **less heat**

Ceramic

- **less conductive**
- **more wear resistant**
- **higher coeff. of friction**

➔ **more heat**

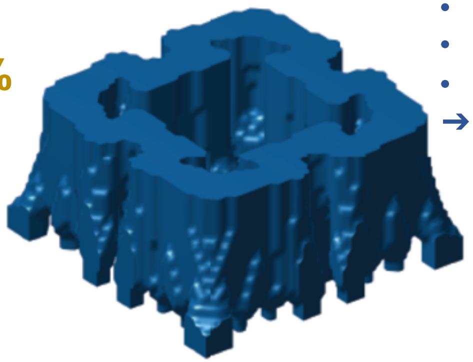


Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

55% reduction in avg. interface temperature rise

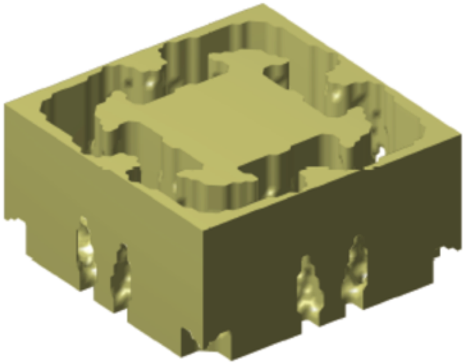
Results shown for metal/ceramic with 50-50 wear layer constraint for target wear performance AND 50-50 domain constraint above the wear layer

50% | 50%
Domain



Metal
- more conductive
- less wear resistant
- lower coeff. of friction

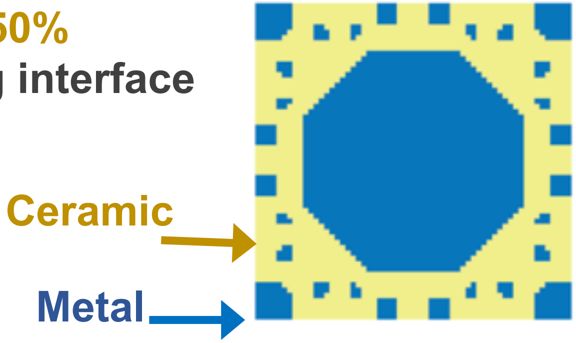
➔ less heat

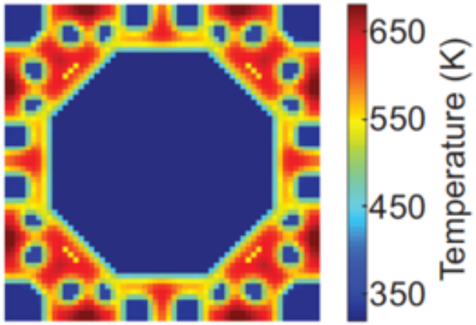


Ceramic
- less conductive
- more wear resistant
- higher coeff. of friction

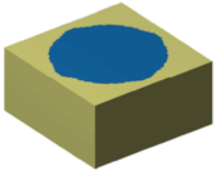
➔ more heat

50% | 50%
Sliding interface





Reference



55% ↓
(obj)

Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

Summary

First step in applying SIMP-based TO for multiphysics – tribological + thermal problems in composite design

More case studies involving wear-constrained or sequentially coupled wear + thermal problems presented

Future directions

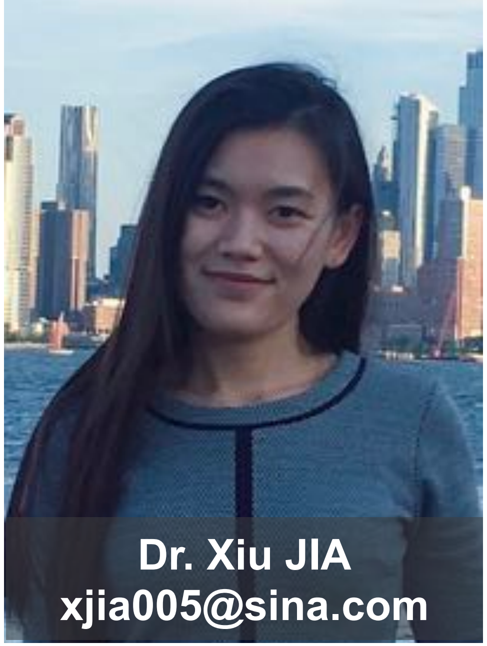
- Multi-objective TO that *simultaneously* addresses wear & frictional heat dissipation
- Optimization of frictional heat dissipation during the *transient run-in wear regime* which involves dramatic changes in contact pressure and surface profile
- Including manufacturing constraints and uncertainties for practical applications.

Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

Topology Optimization of Tribological Composites for Multifunctional Performance at Sliding Interfaces

7th TOP Webinar
2020-11-24

Prof. Natasha VERMAAK
vermaak@lehigh.edu



Dr. Xiu JIA
xjia005@sina.com

BASED ON: Xiu Jia, Tomas Grejtak, Brandon Krick, and Natasha Vermaak. "Topology optimization of tribological composites for multifunctional performance at sliding interfaces." Composites Part B: Engineering 199 (2020): 108209. *https://doi.org/10.1016/j.compositesb.2020.108209*

Grant #1538125