Selection Applied to the Design of Composite Materials

New approach to the development of composites

«Constitutive equations»

Equations ruling the properties of composites depending on those of constituents

- ***Attention to the «architecture»***
- ***Attention to anisotropy***

$$E_L = E_F \cdot V_F + E_M \cdot (1 - V_F) = E_{MAX}$$

$$E_T = \frac{E_M \cdot E_F}{(1 - V_F) \cdot E_F + V_F \cdot E_M} = E_{MIN}$$

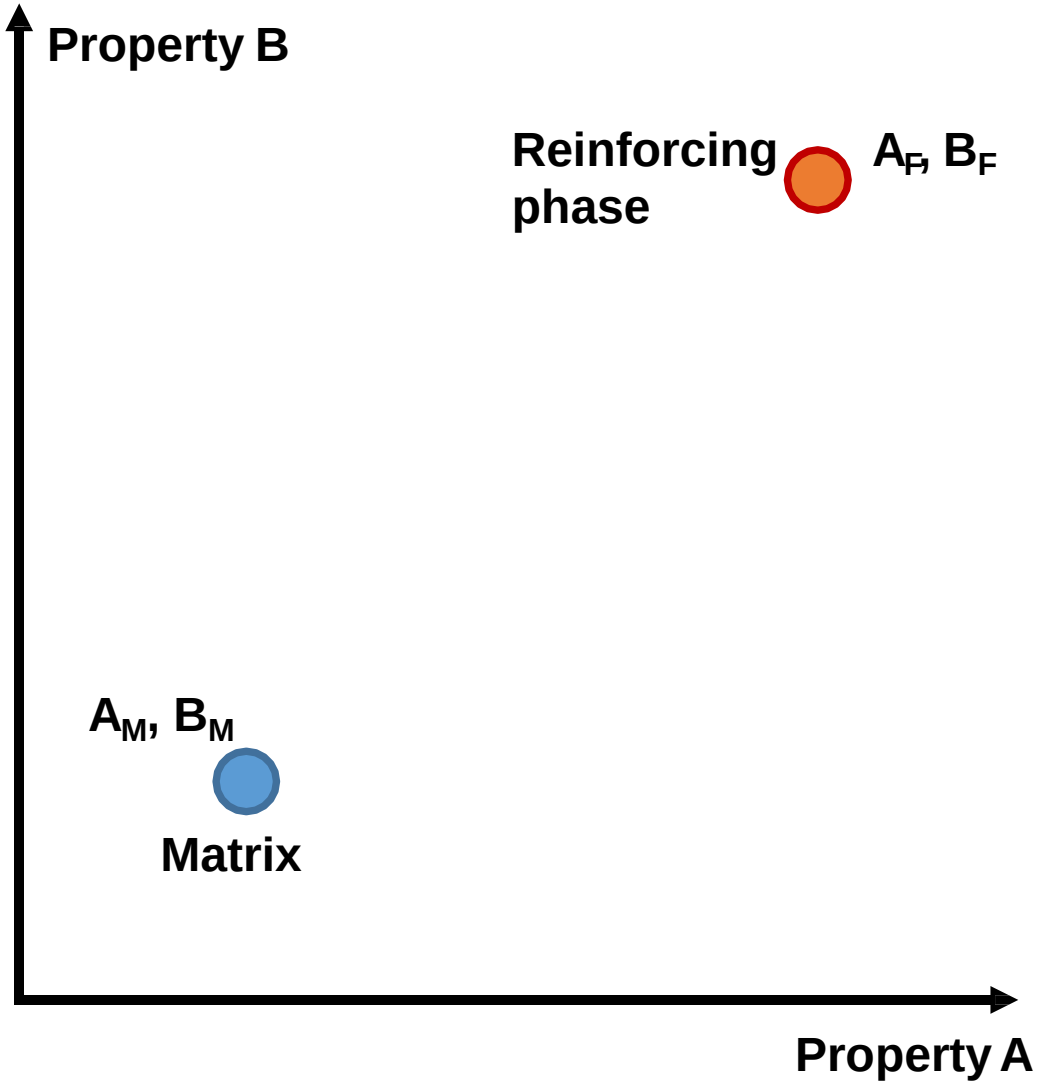
$$\rho = \rho_F \cdot V_F + \rho_M \cdot (1 - V_F)$$

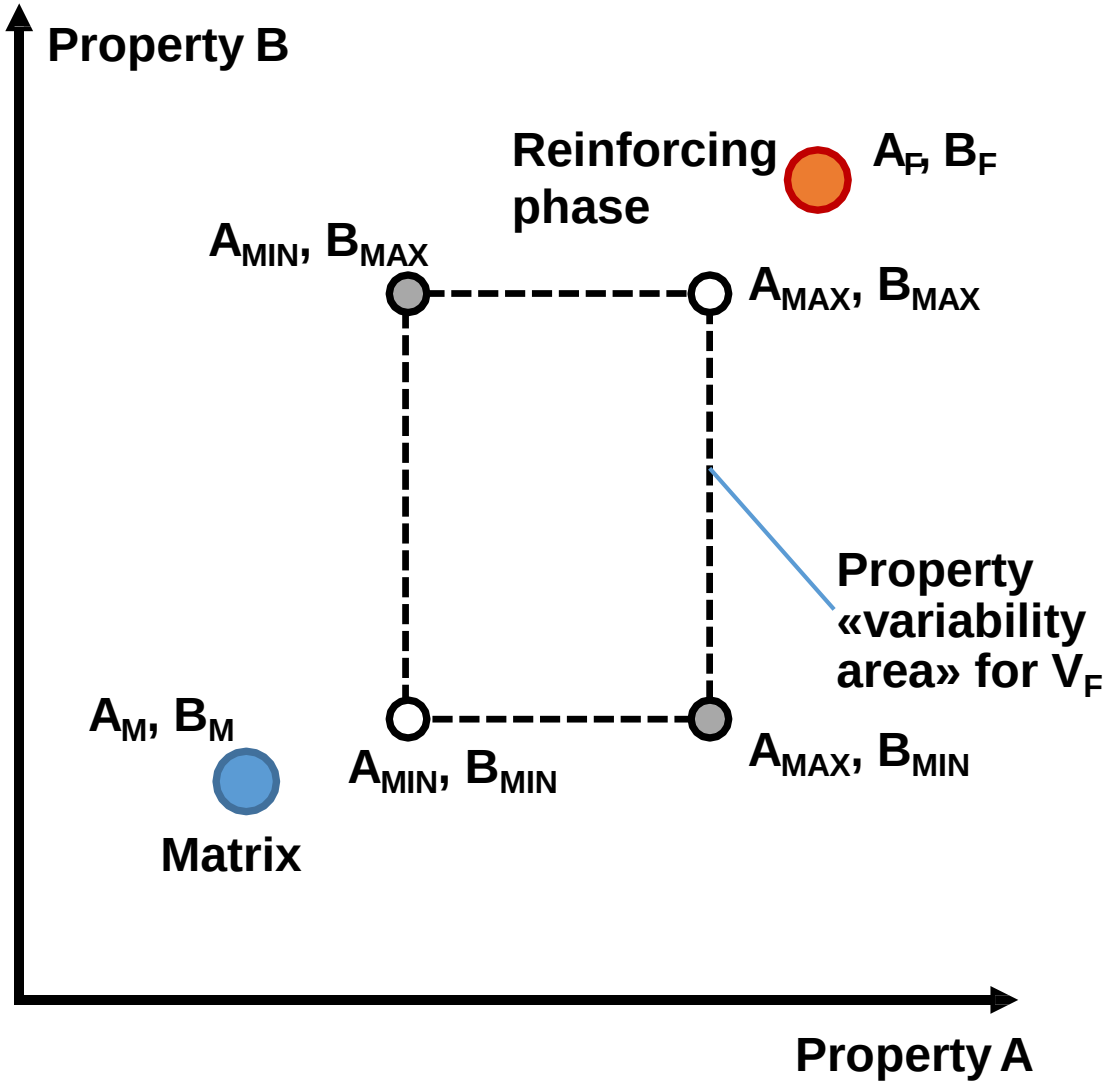
In general:

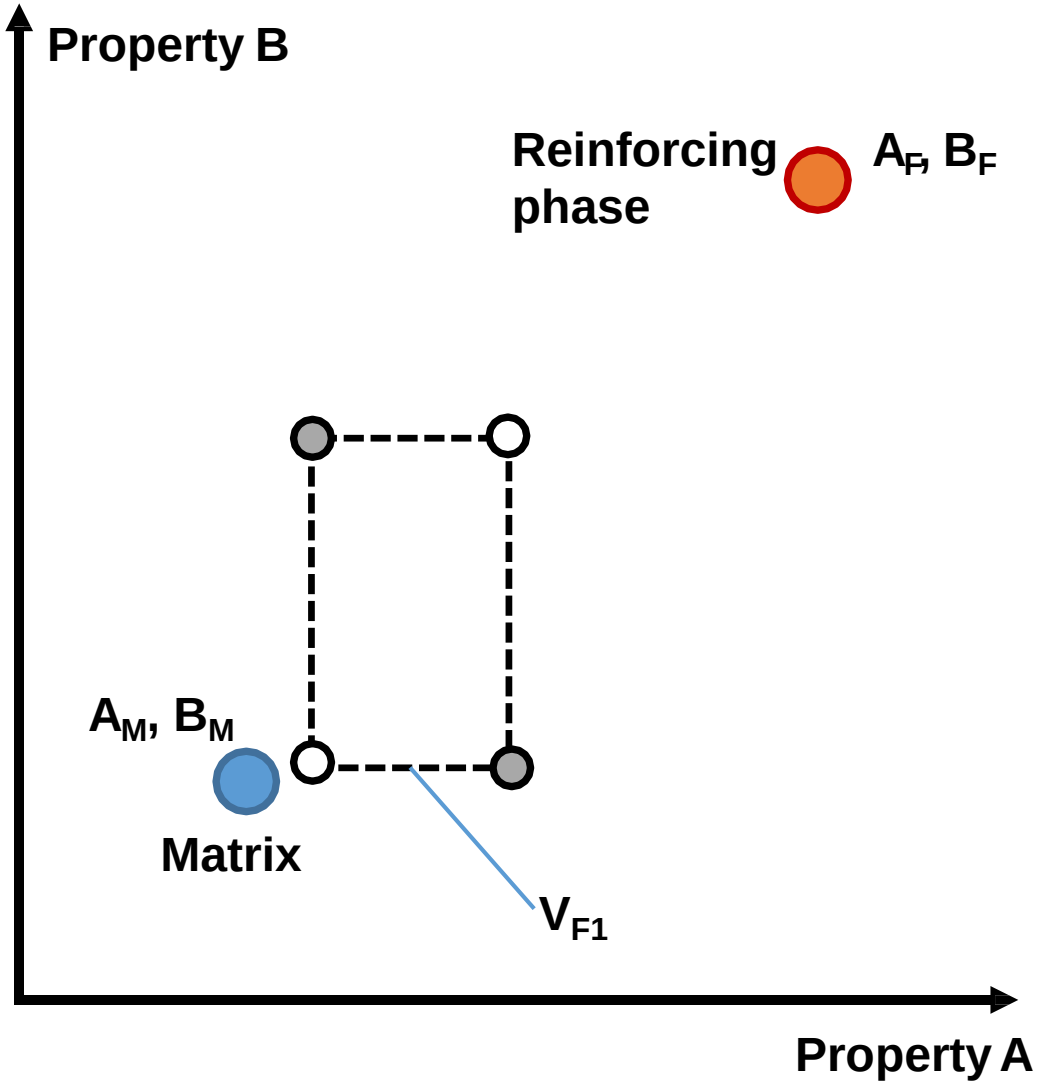
$A_{MAX}=A_{MAX}(A_M,A_F,V_F)$ $A_{MIN}=A_{MIN}(A_M,A_F,V_F)$

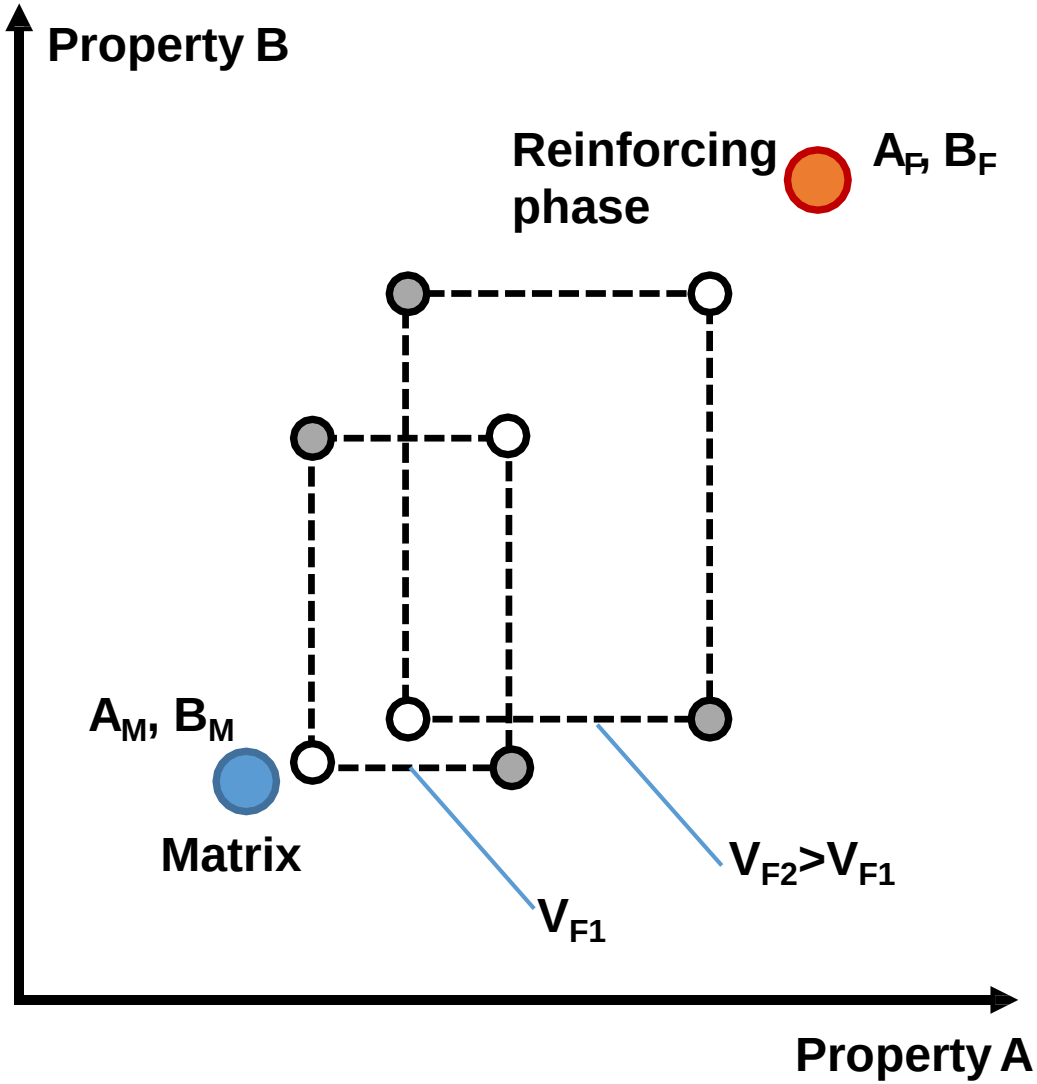
$B_{MAX}=B_{MAX}(B_M,B_F,V_F)$ $B_{MIN}=B_{MIN}(B_M,B_F,V_F)$

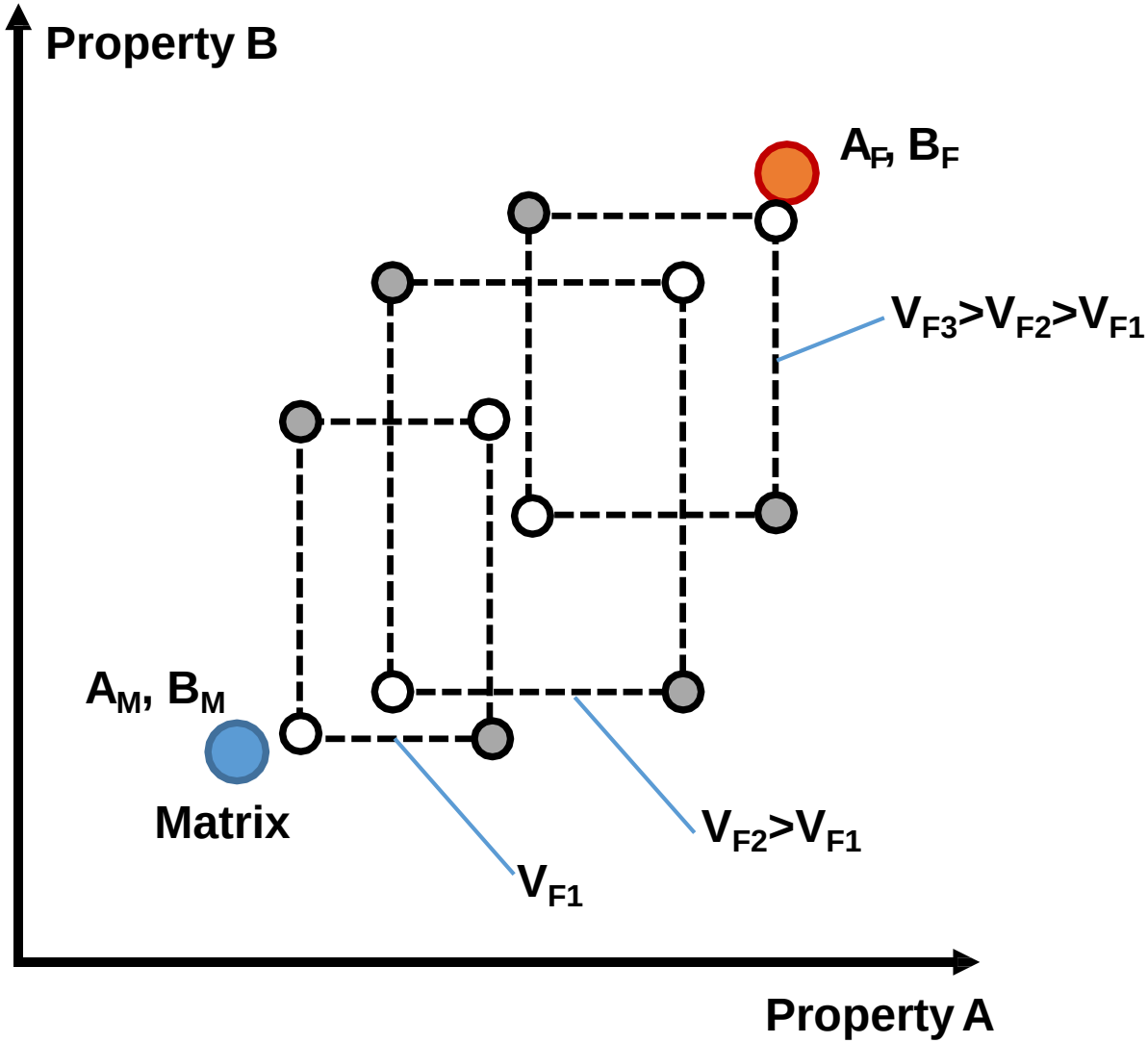
Very simple graphical representation

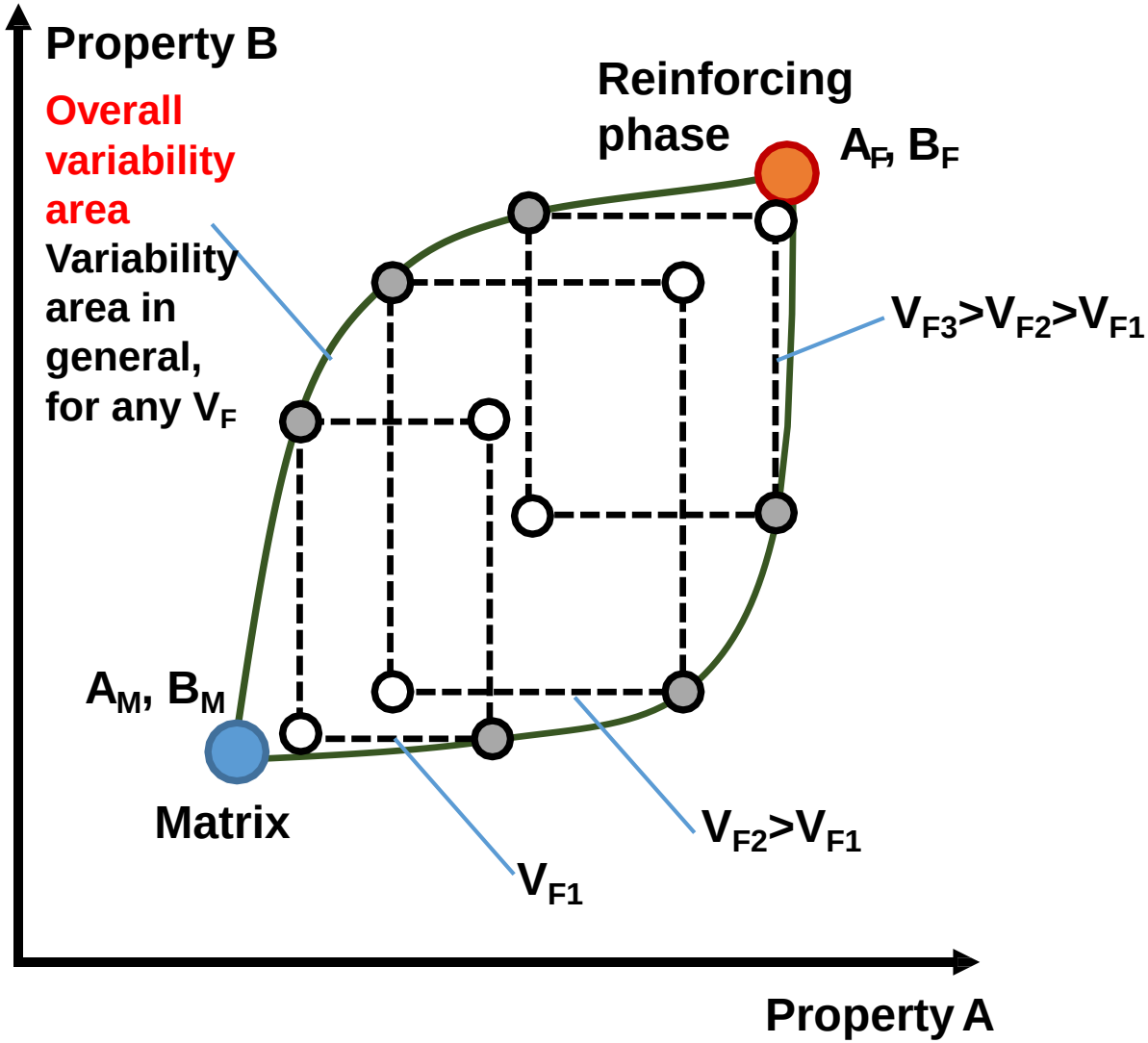

Property B
Reinforcing phase
A_F, B_F
A_M, B_M
Matrix
Property A

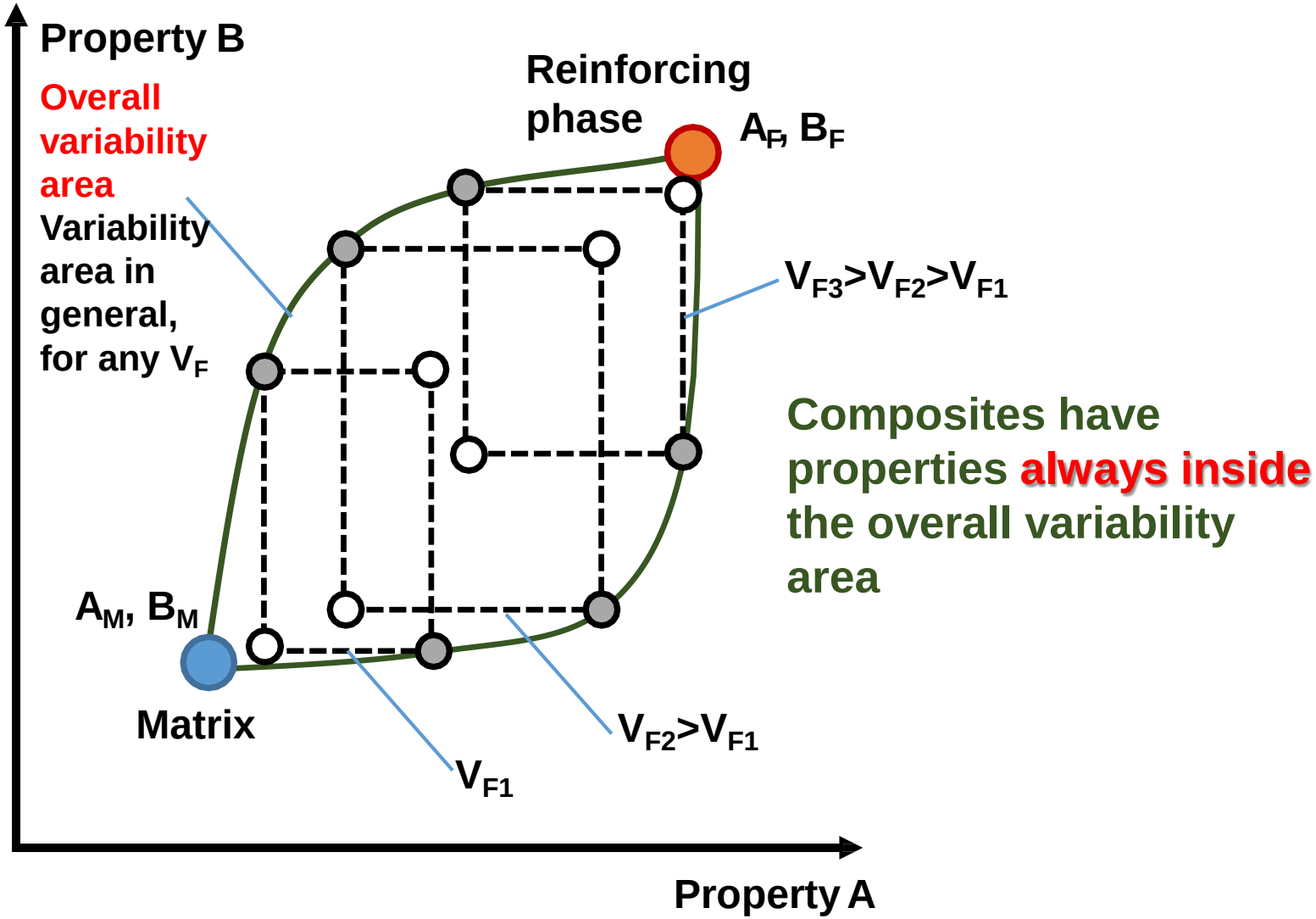

Property B
Reinforcing phase
A_F, B_F
A_{MIN}, B_{MAX}
A_{MAX}, B_{MAX}
Property «variability area» for V_F
A_M, B_M
A_{MIN}, B_{MIN}
A_{MAX}, B_{MIN}
Matrix
Property A


Property B
Reinforcing phase
A_F, B_F
A_M, B_M
Matrix
V_{F1}
Property A

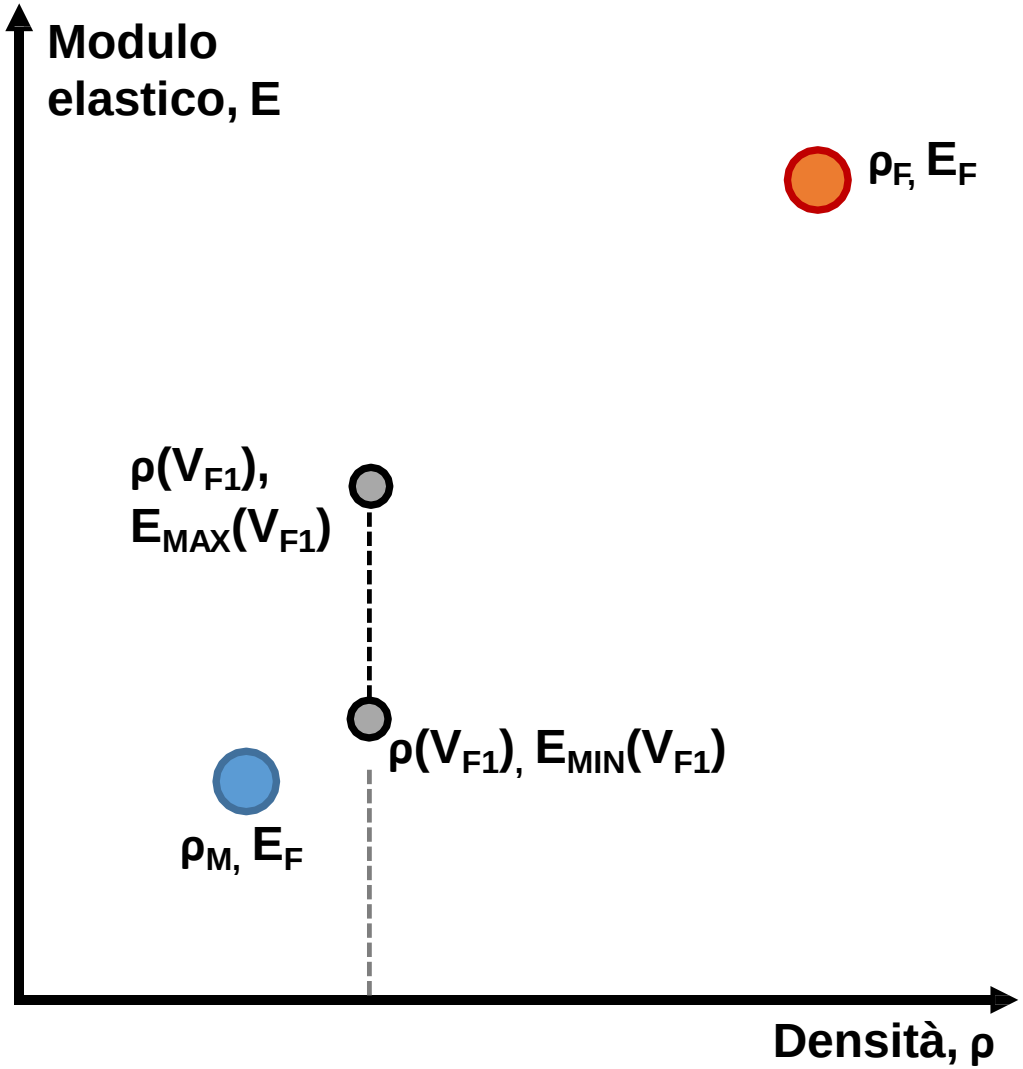

Property B
Reinforcing phase
A_F, B_F
A_M, B_M
Matrix
V_{F1}
$V_{F2}>V_{F1}$
Property A


Property B
A_F, B_F
$V_{F3}>V_{F2}>V_{F1}$
A_M, B_M
Matrix
V_{F1}
$V_{F2}>V_{F1}$
Property A

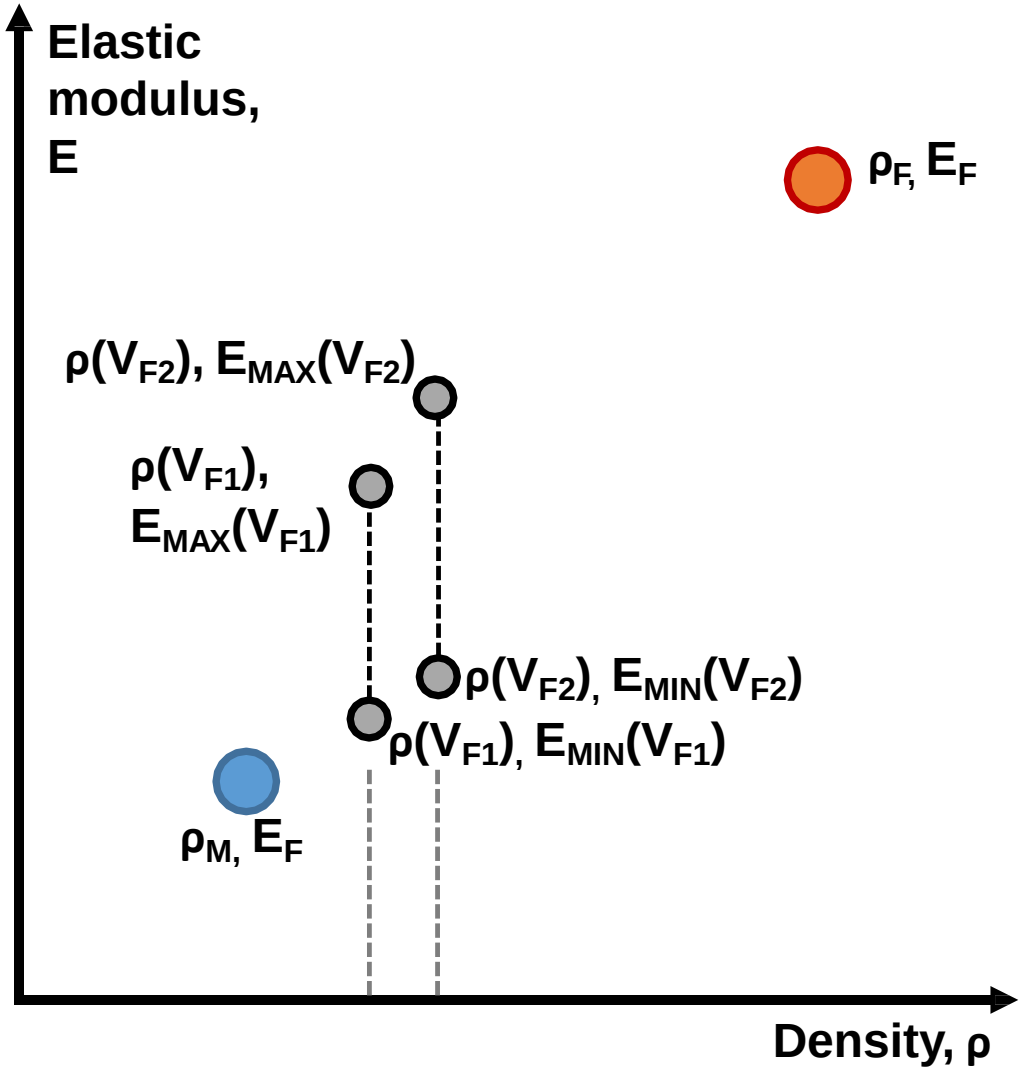

Property B
Overall variability area
Variability area in general, for any V_F
Reinforcing phase
A_F, B_F
$V_{F3}>V_{F2}>V_{F1}$
A_M, B_M
Matrix
V_{F1}
$V_{F2}>V_{F1}$
Property A



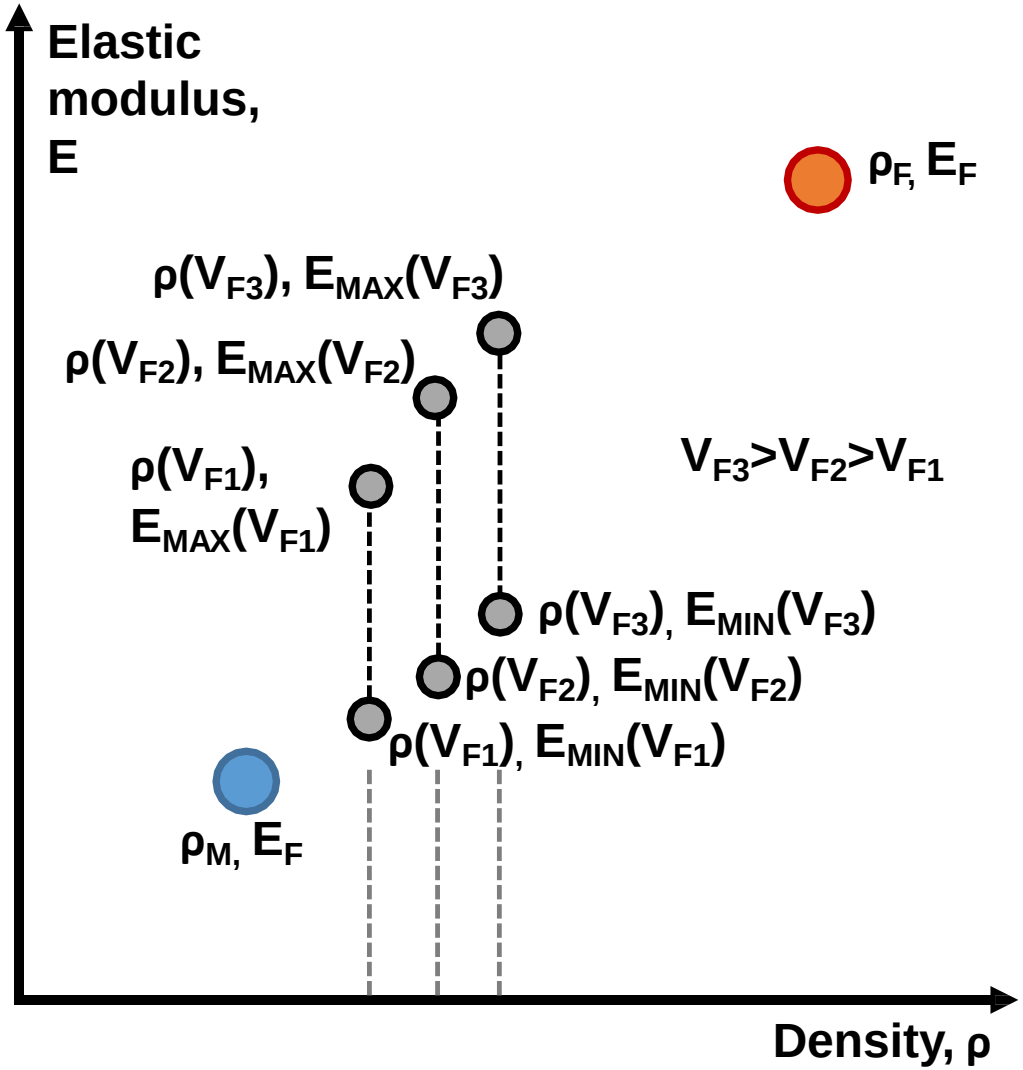
Composites have properties **always inside** the overall variability area



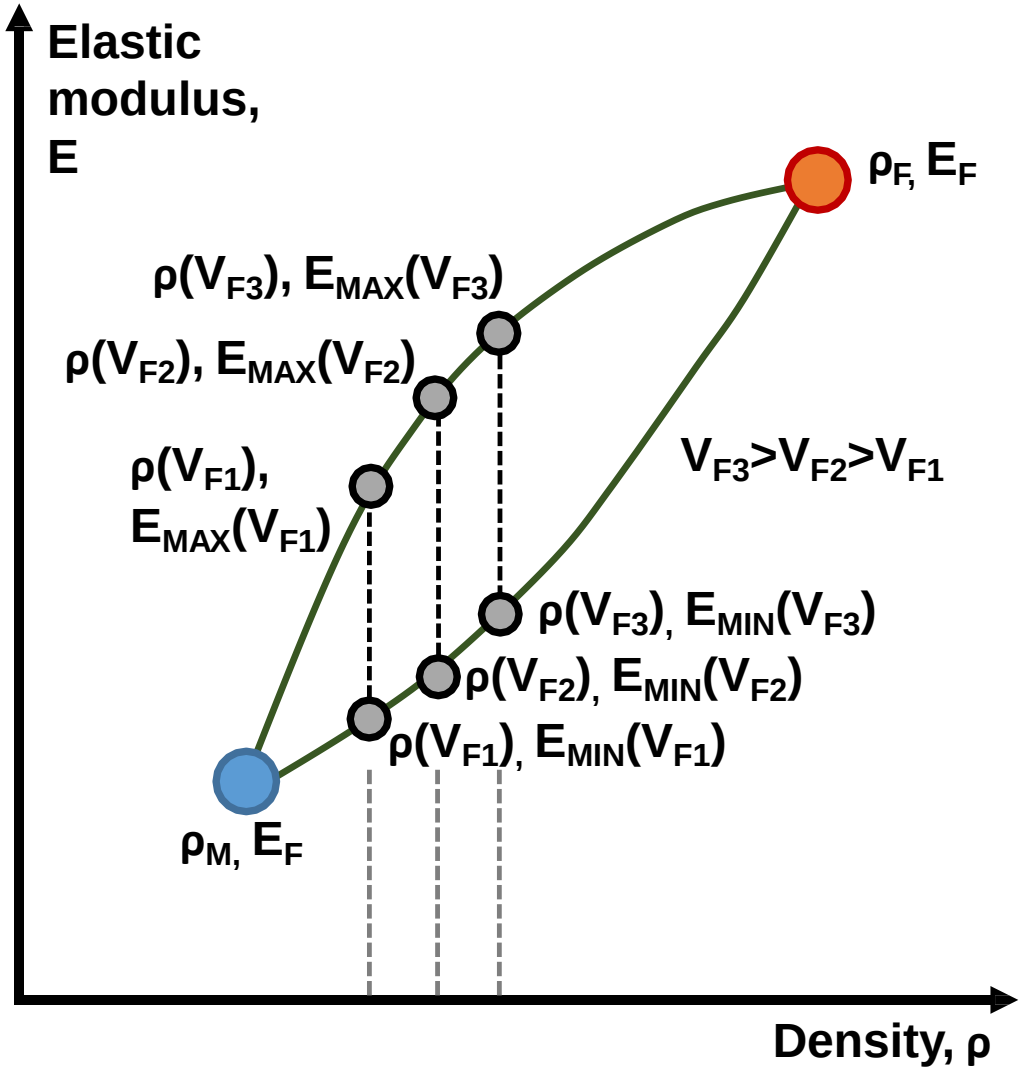
Density does not depend on the architecture: only one value for a given volume fraction
Simplified graph



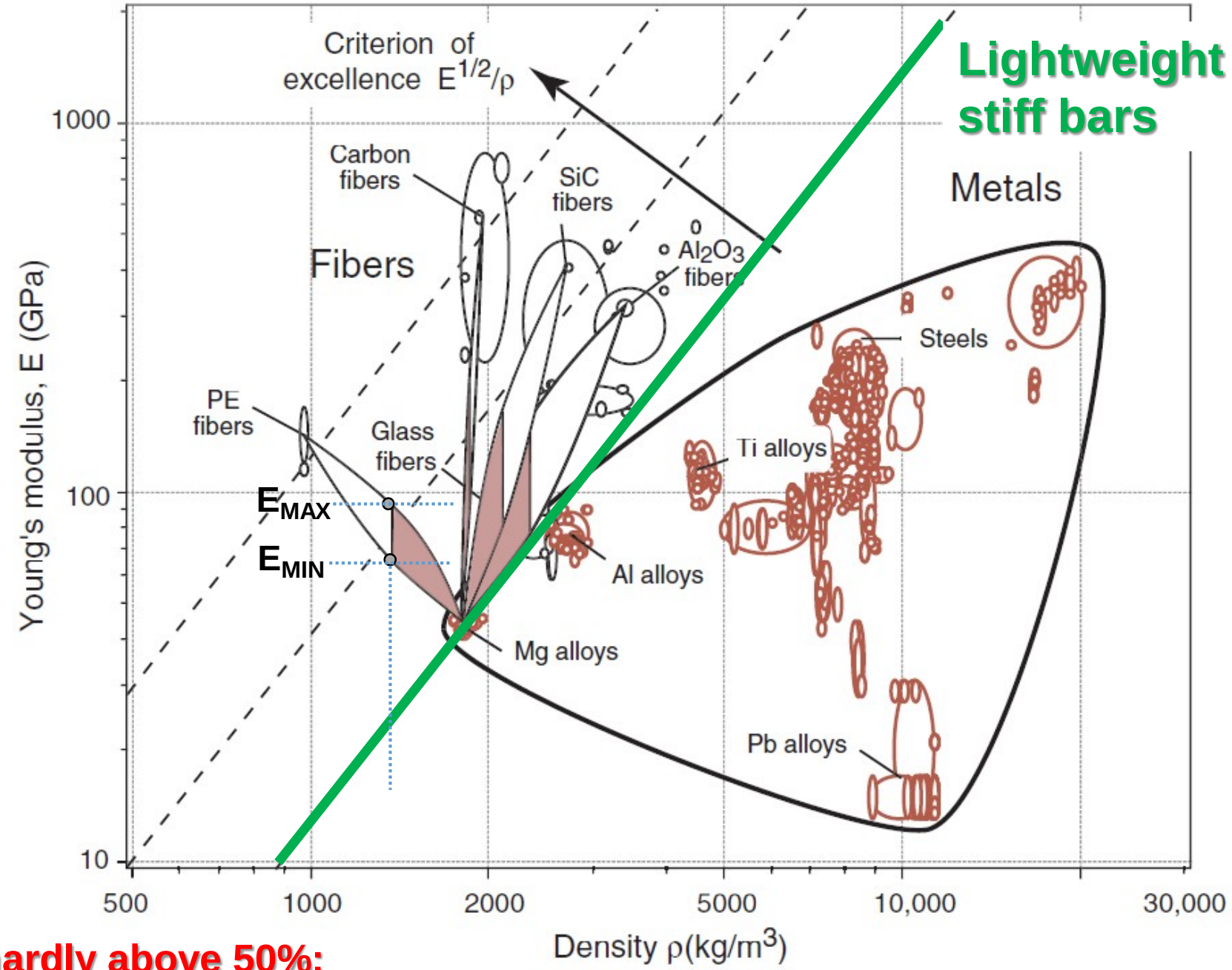
Density does not depend on the architecture: only one value for a given volume fraction
Simplified graph



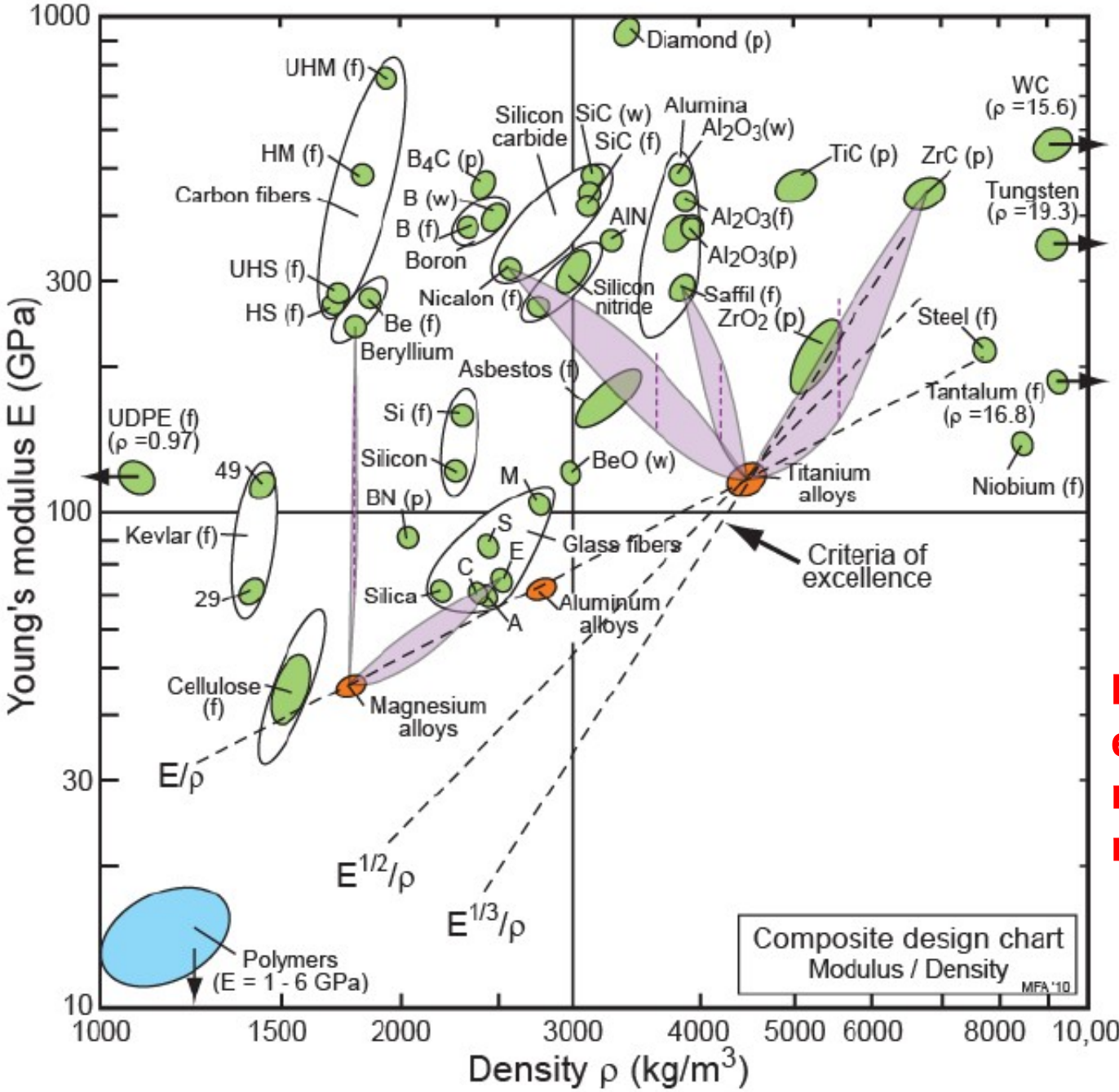
Density does not depend on the architecture: only one value for a given volume fraction
Simplified graph



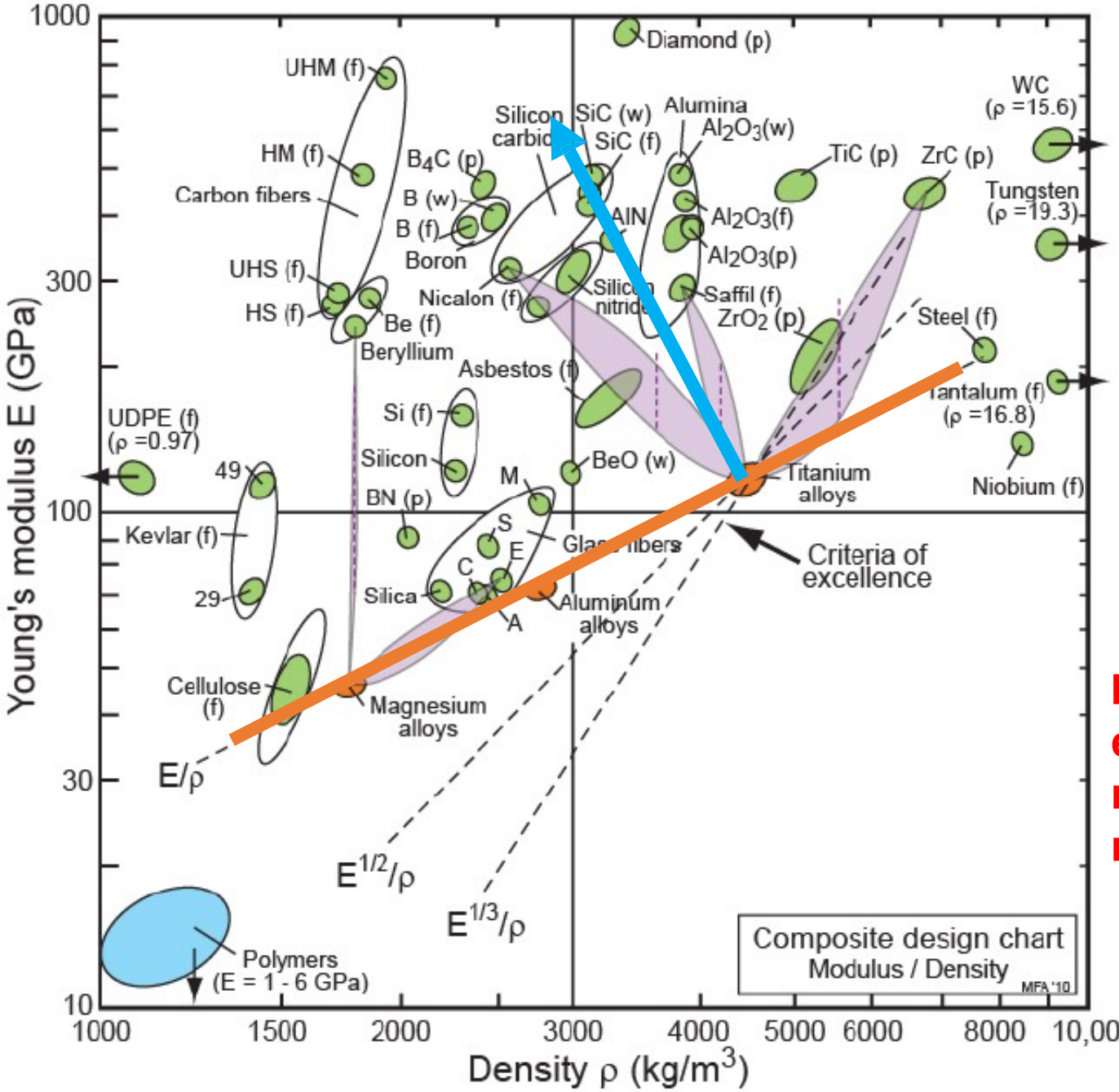
Density does not depend on the architecture: only one value for a given volume fraction
Simplified graph



V_F hardly above 50%: «truncated» variability areas

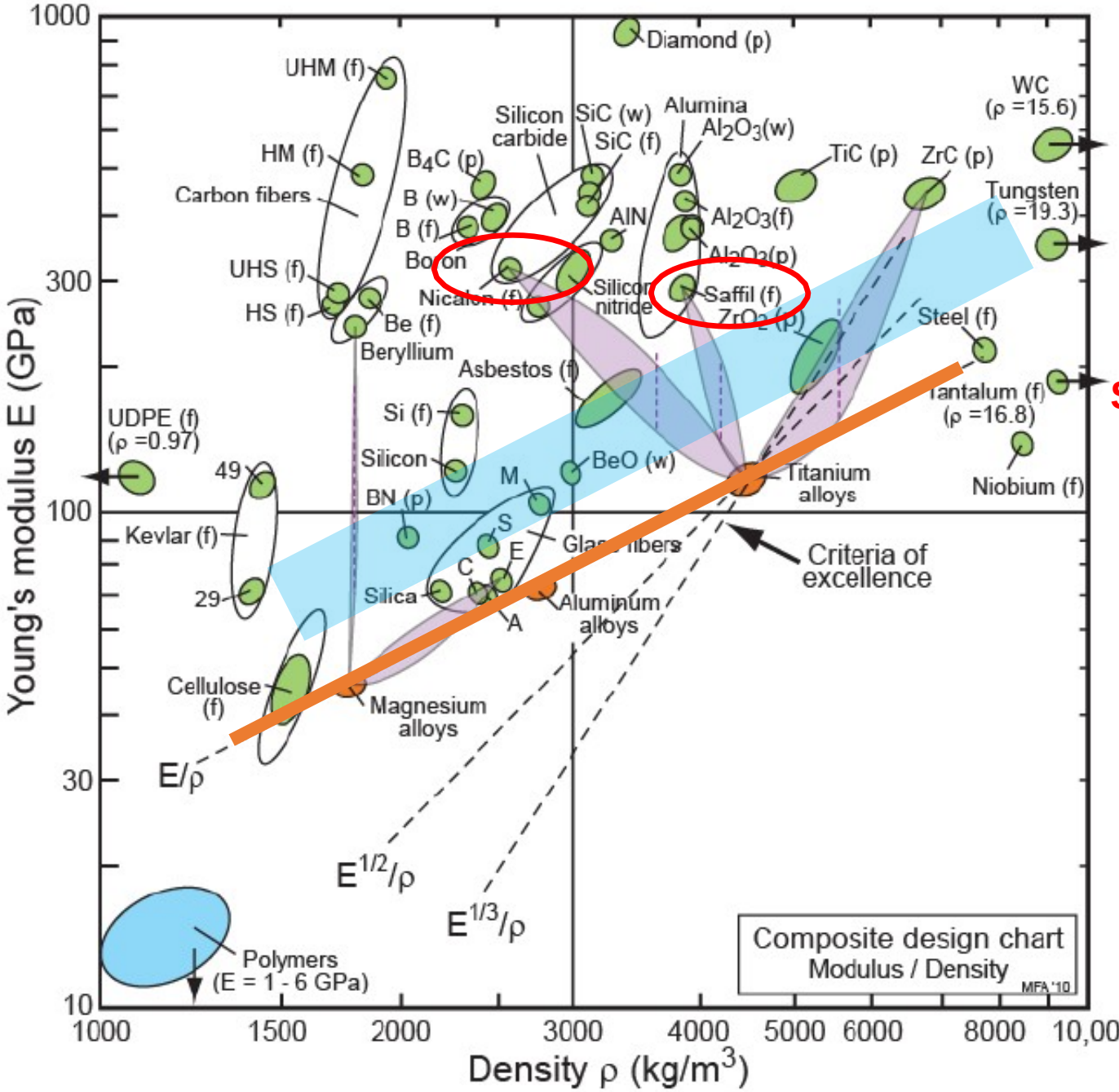


Looking for efficient reinforcing materials for Ti matrices

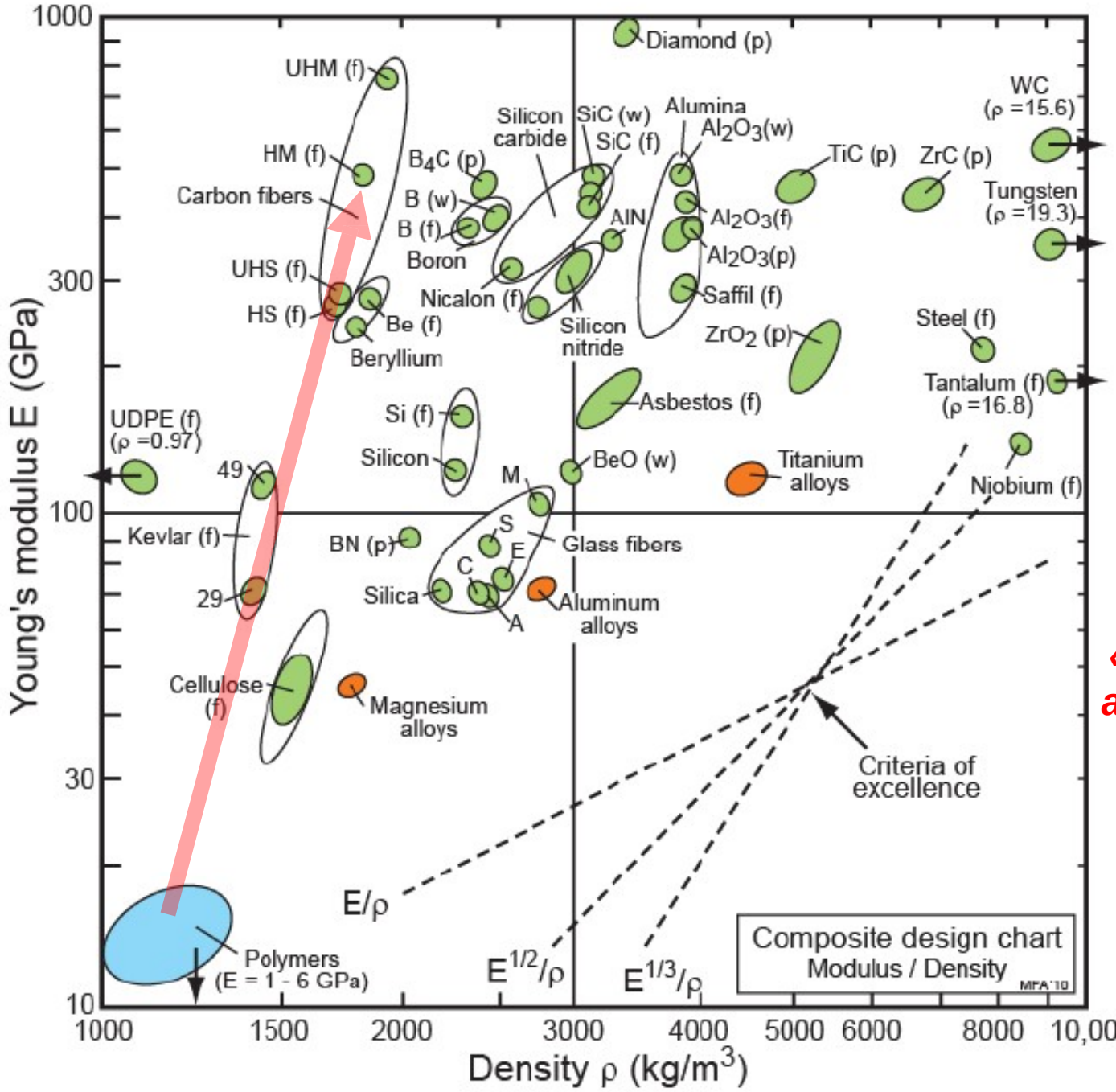


Materials placed «orthogonally», on the basis of the selection line (for a given mechanical configuration) are attractive

Looking for efficient reinforcing materials for Ti matrices

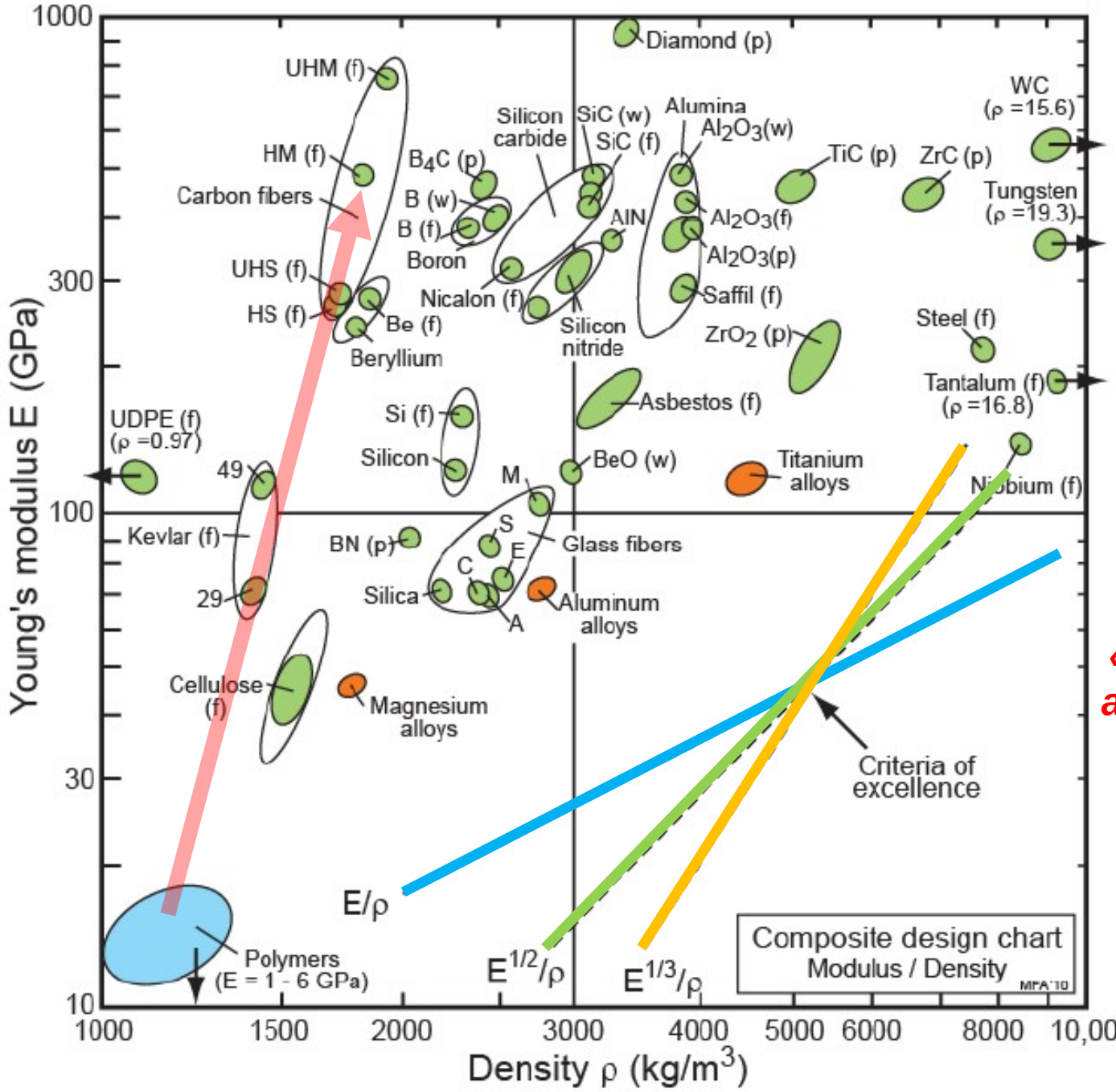


SiC (Nicalon) and alumina (Saffil) fibres are OK

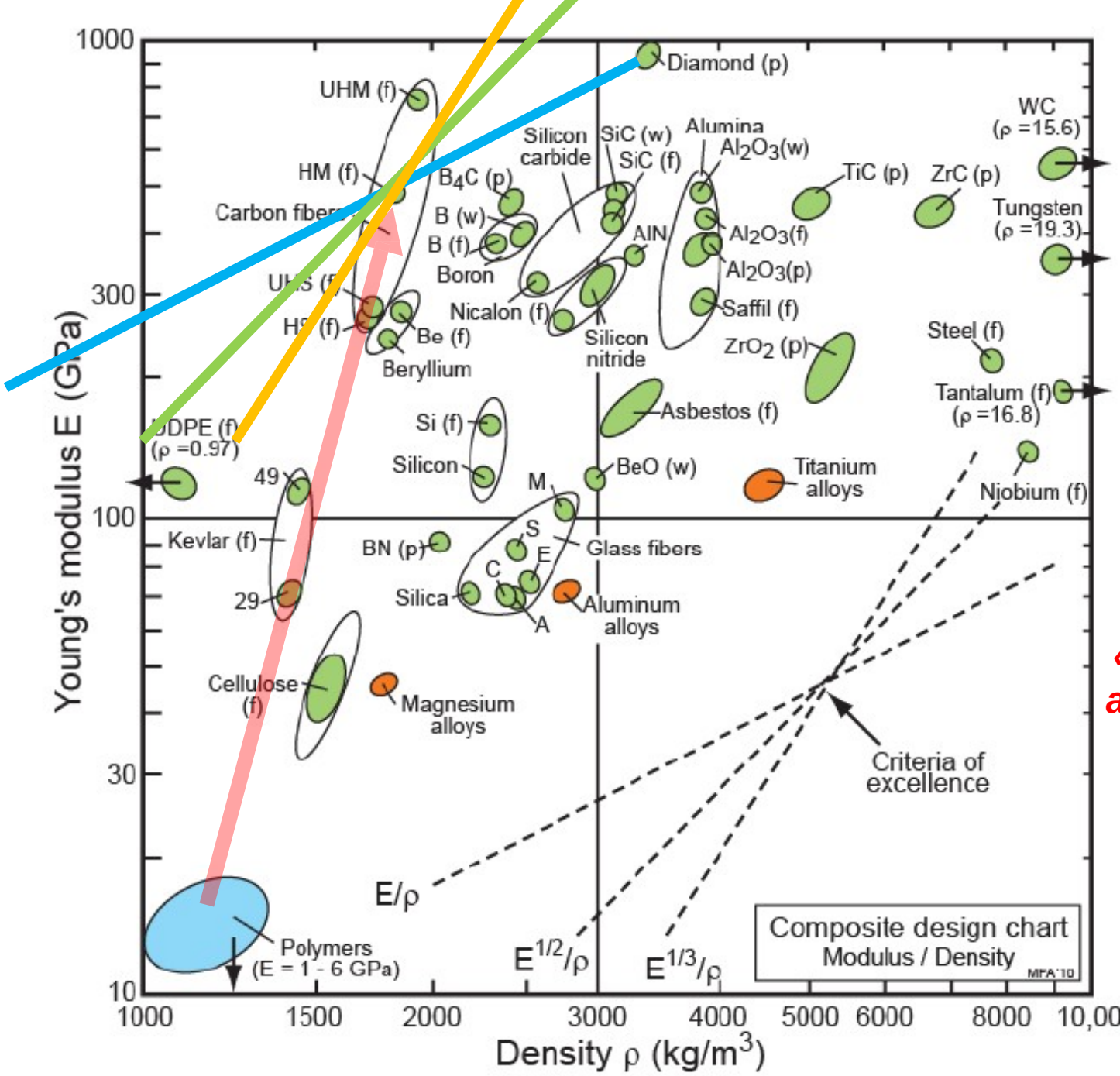


Carbon fibres

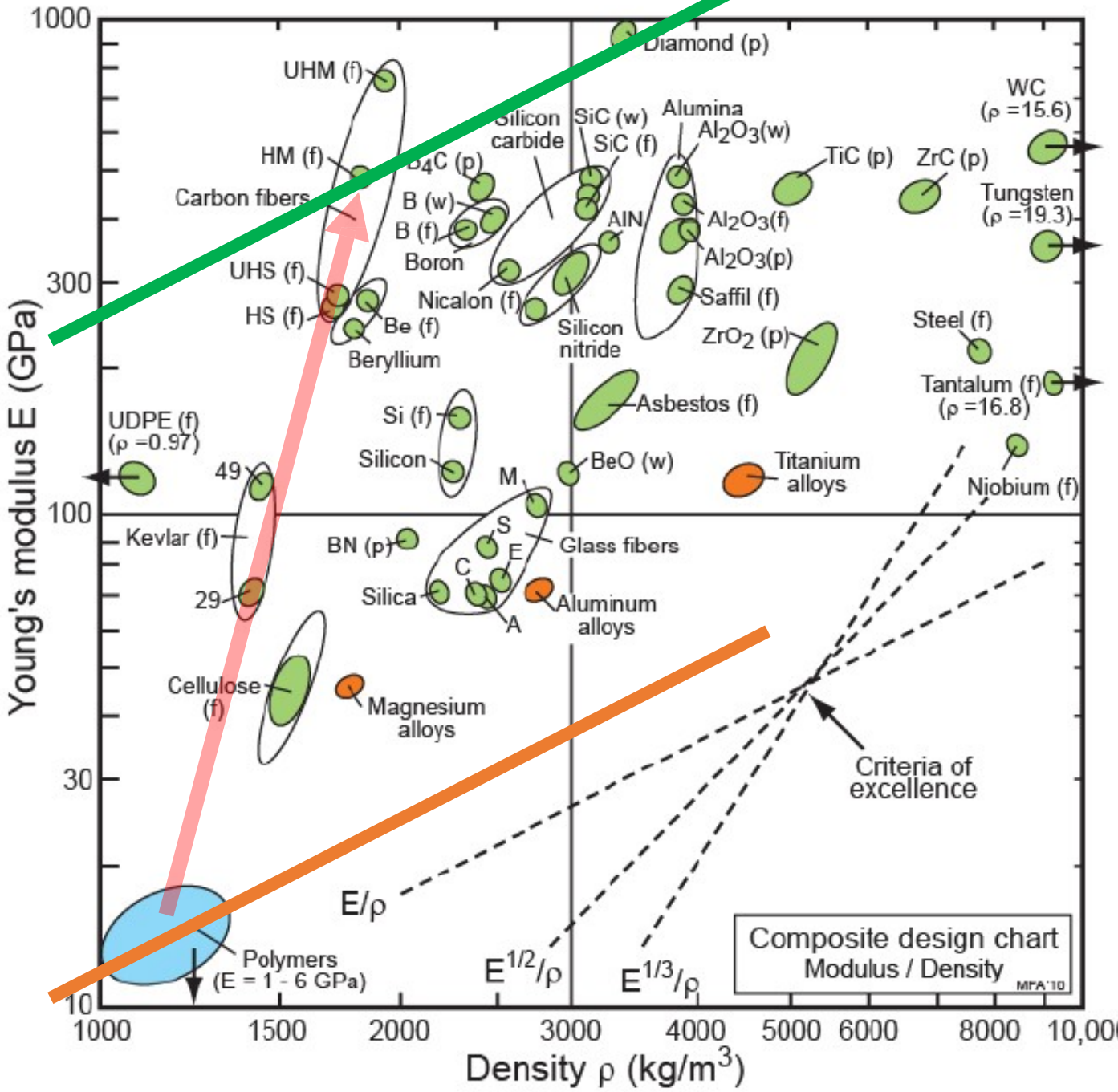
Not perfectly «orthogonal», but in any case possessing high values for any index



Carbon fibres
Not perfectly «orthogonal», but in any case possessing high values for any index

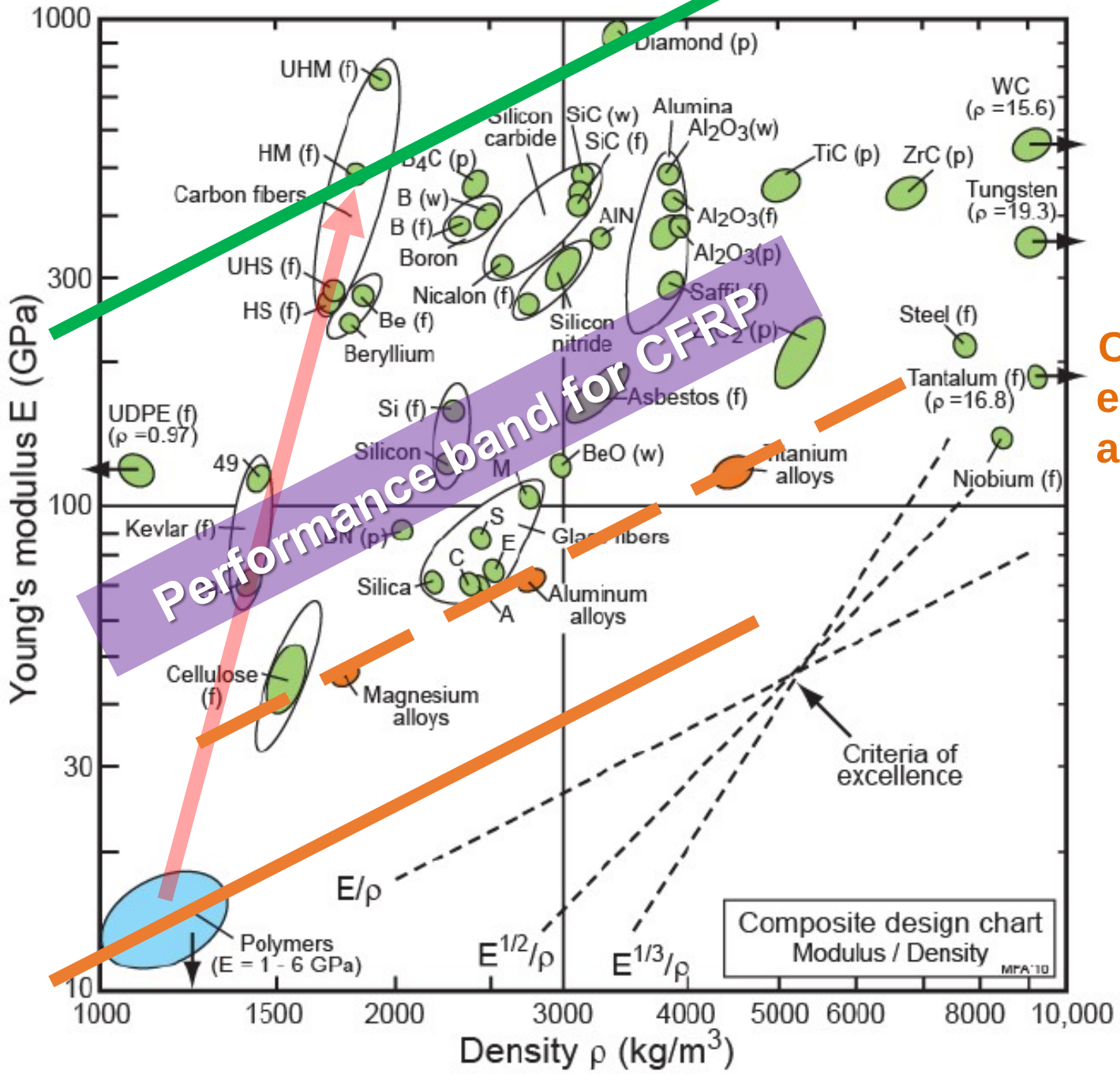


Carbon fibres
Not perfectly «orthogonal», but in any case possessing high values for any index



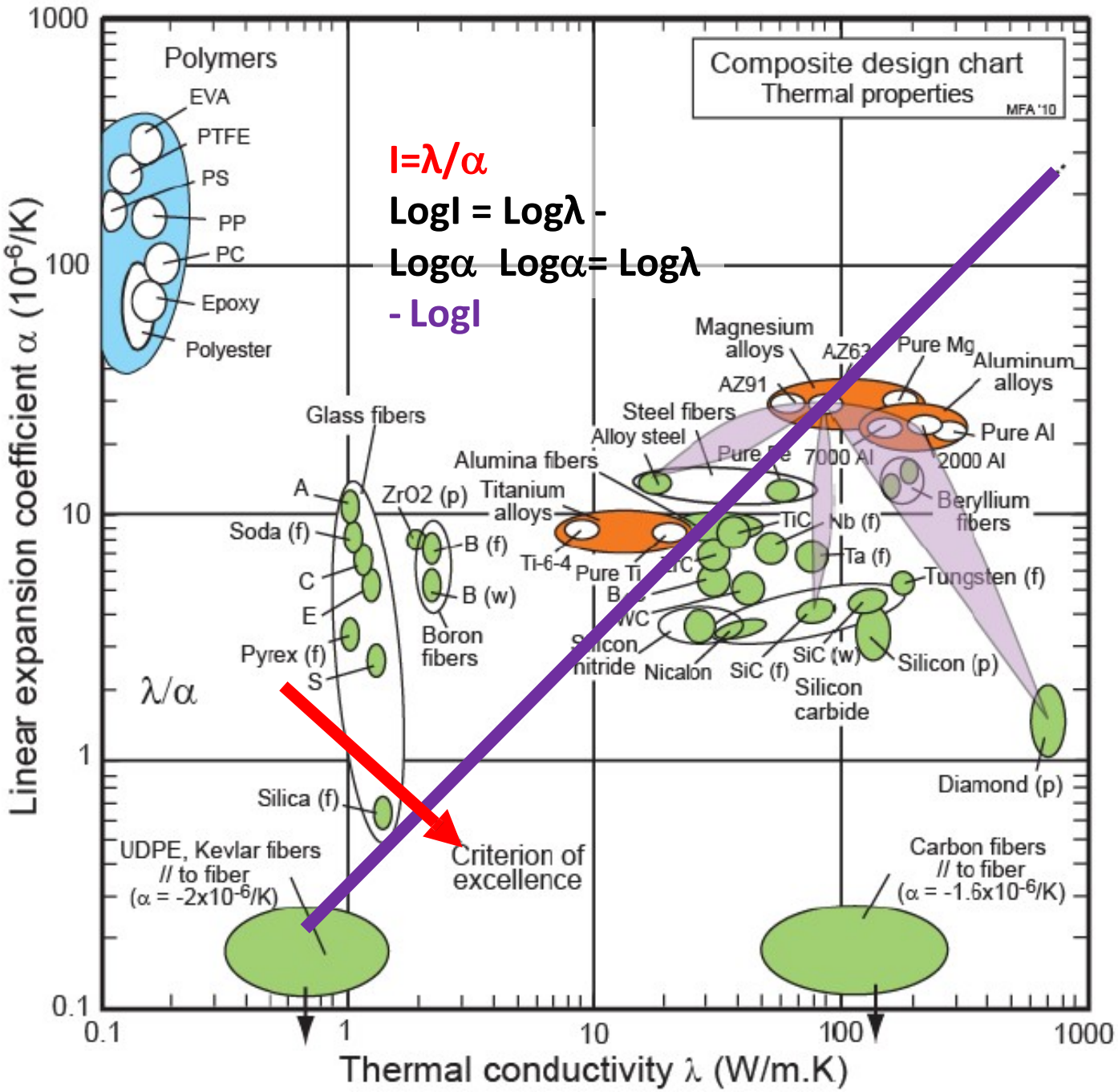
Tie-rods

Dramatic improvement of polymer matrices



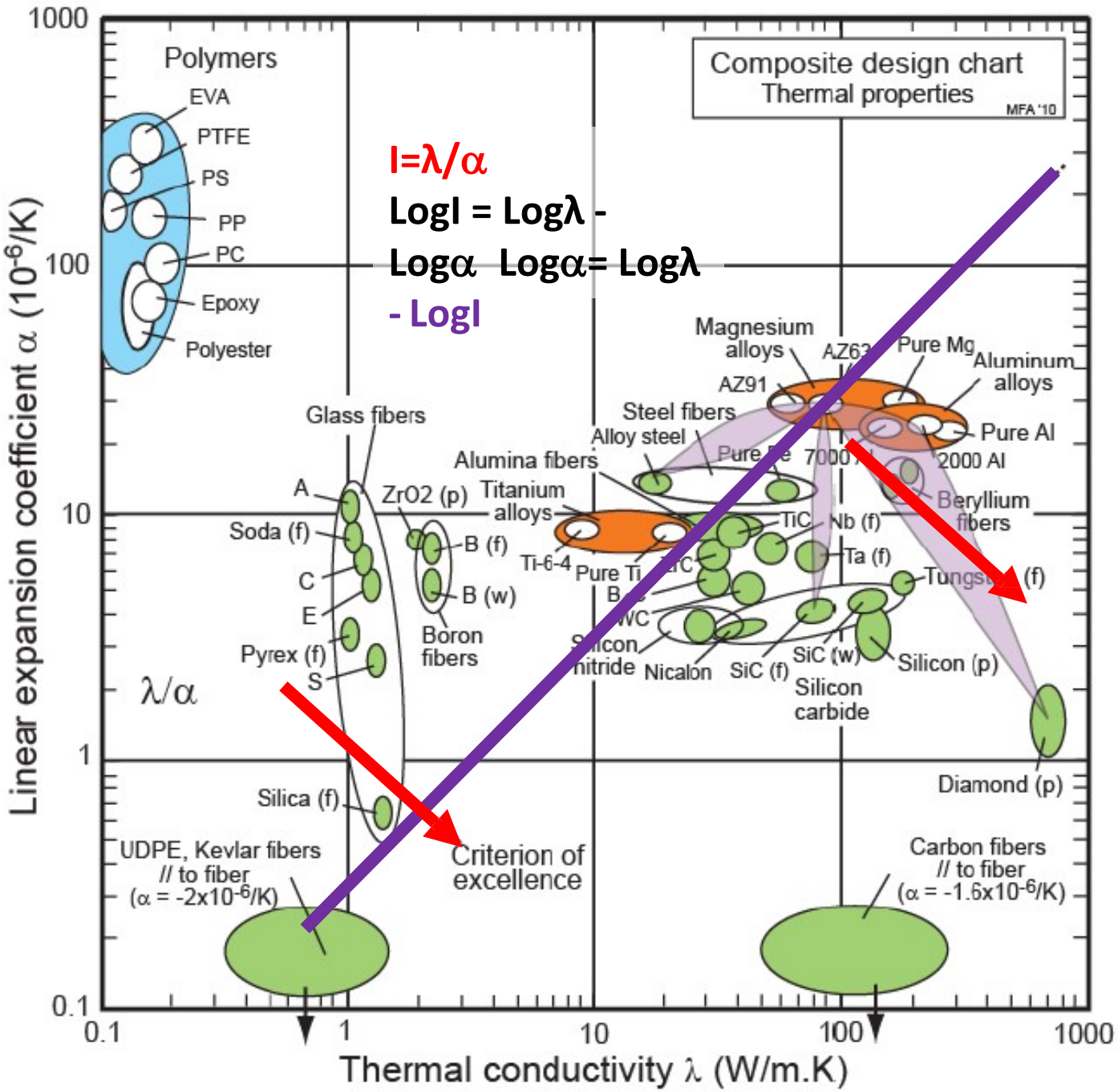
CFRP more efficient than Al alloys

Tie-rods
Dramatic improvement of polymer matrices



Thermal design

Reducing thermal distortions



Thermal design
Reducing thermal distortions

Al & Mg alloys
Diamond placed orthogonally: are these composites actually feasible?

Diamond/Al metal matrix composites formed by the pressureless metal infiltration process

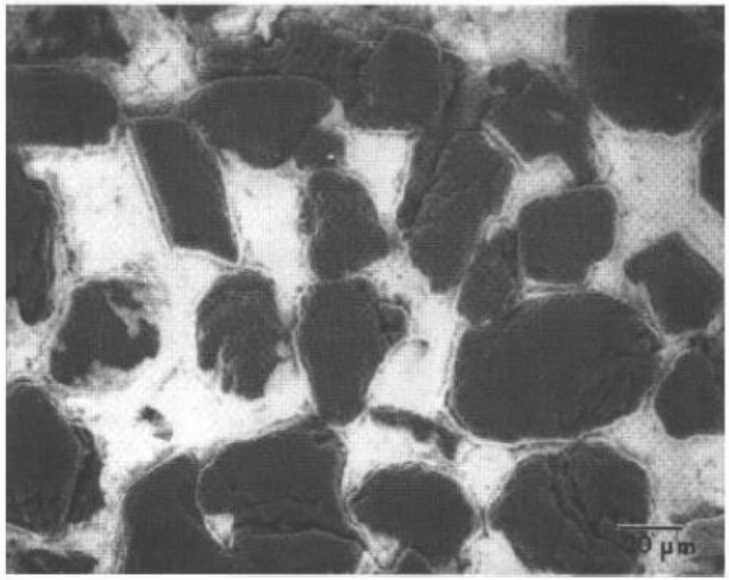
William B. Johnson and B. Sonuparlak
Lanxide Corporation, 1300 Marrows Road, P.O. Box 6077, Newark, Delaware 19714-6077

(Received 12 June 1992; accepted 29 December 1992)

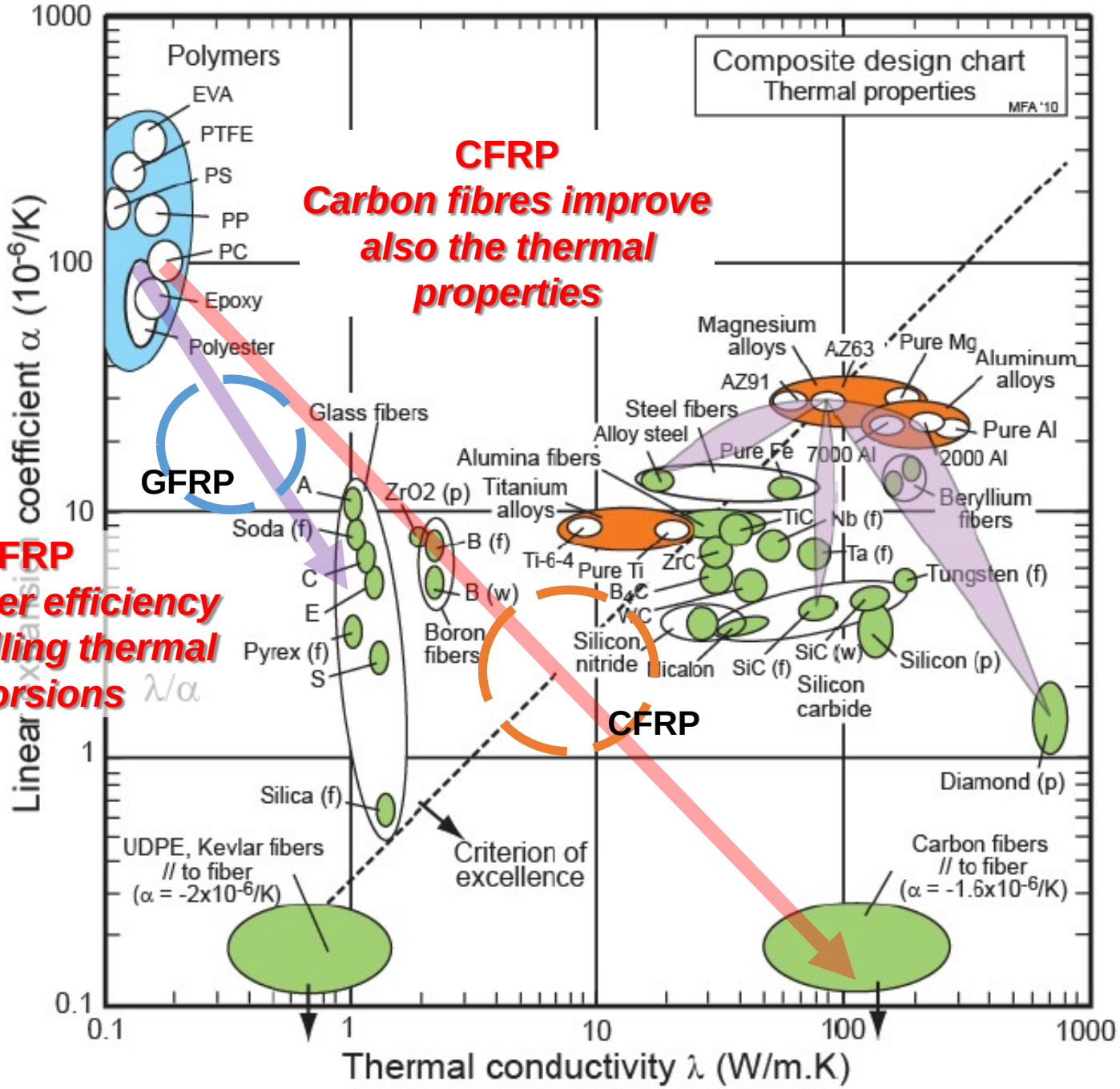
Diamond particles are unique fillers for metal matrix composites because of their extremely high modulus, high thermal conductivity, and low coefficient of thermal expansion. Diamond reinforced aluminum metal matrix composites were prepared using a pressureless metal infiltration process. The diamond particulates are coated with SiC prior to infiltration to prevent the formation of Al_4C_3, which is a product of the reaction between aluminum and diamond. The measured thermal conductivity of these initial diamond/Al metal matrix composites is as high as 259 W/m-K. The effects of coating thickness on the physical properties of the diamond/Al metal matrix composite, including Young's modulus, 4-point bend strength, coefficient of thermal expansion, and thermal conductivity, are presented.

Al & Mg alloys
Diamond placed orthogonally: are these composites actually feasible?

Yes (see paper for Aluminum); attention to the inferface [SiC coating to prevent reaction]



Example of composites «designed» on the basis of material selection criteria



CFRP
Carbon fibres improve also the thermal properties

GFRP

GFRP
Much lower efficiency in controlling thermal distorsions

CFRP

CFRP comparable to Al & Mg alloys in terms of sensitivity to thermal distorsions

High performance cellular structures

$$\frac{E}{E_S} \approx (1-P)^2 = \left(\frac{\rho}{\rho_S}\right)^2$$

Relative density

Open-celled foams

$$\frac{\sigma_{cr}}{\sigma_{fs}} \approx 0.2(1-P)^{3/2}$$

Open-celled foams

P = porosity

Constitutive equations for foams

Closed cells: contributions from membranes (=cell walls)

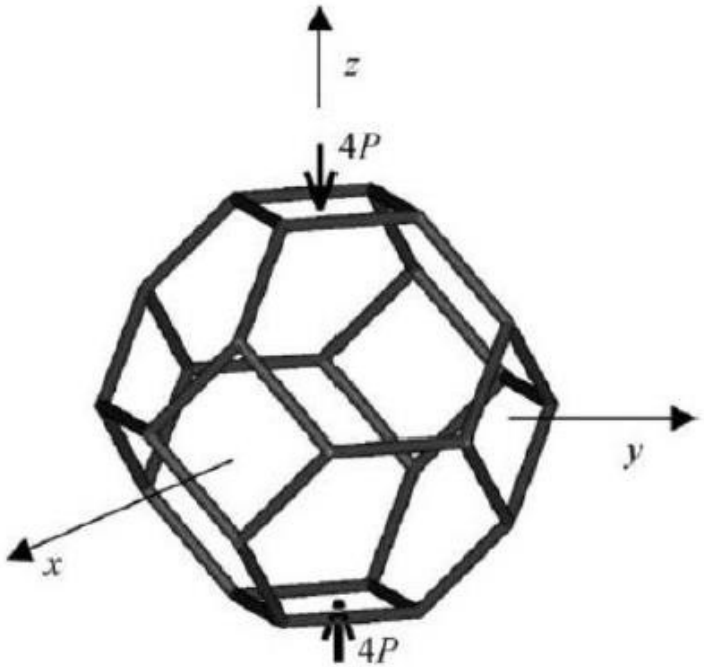
Φ = quantity of solid at the cell edges

$$\frac{E}{E_S} \approx \phi^2(1-P)^2 + (1-\phi)(1-P)$$

Foams with closed cells

$$\frac{\sigma_{cr}}{\sigma_{fs}} \approx 0.2[\phi(1-P)]^{3/2} + (1-\phi)(1-P)$$

Foams with closed cells

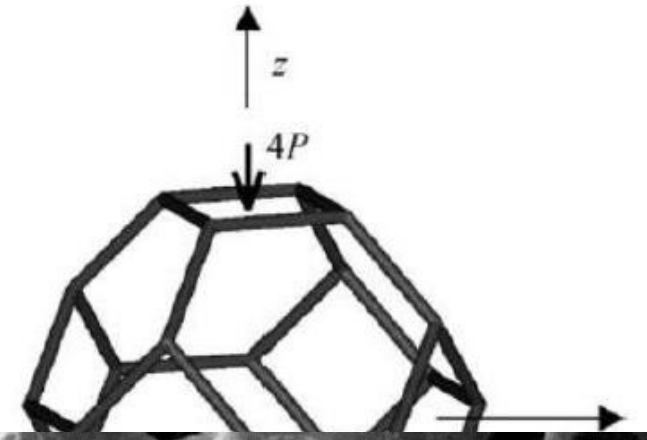


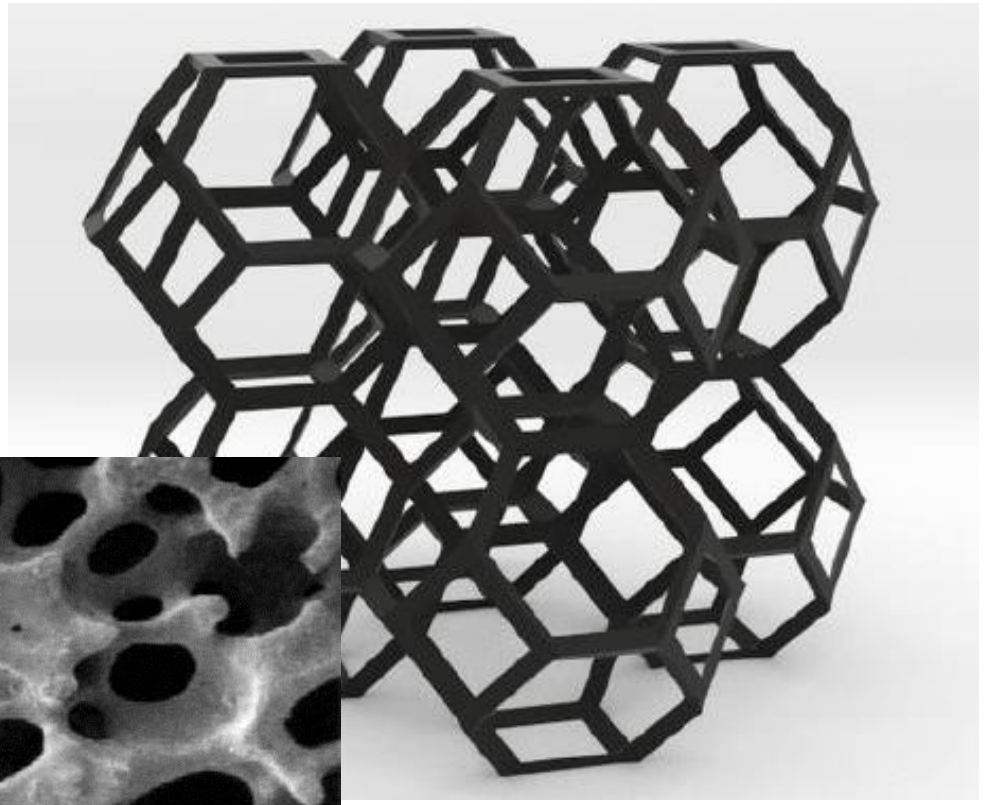
Ideal open-celled structure with multiple polyhedral modular units

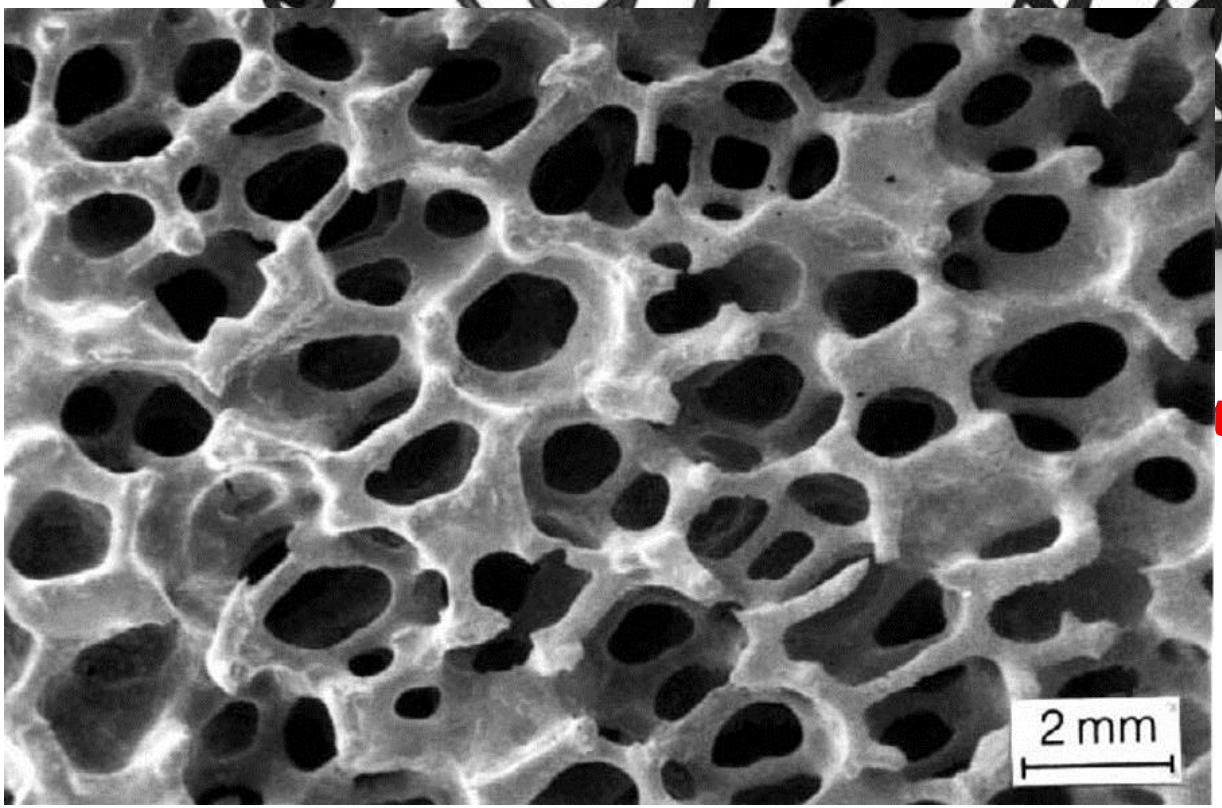
Solid only on edges
[Kelvin foam]



Actual cells are not regular, but they are certainly polyhedral







tual cells are not regular, but they are certainly polyhedral

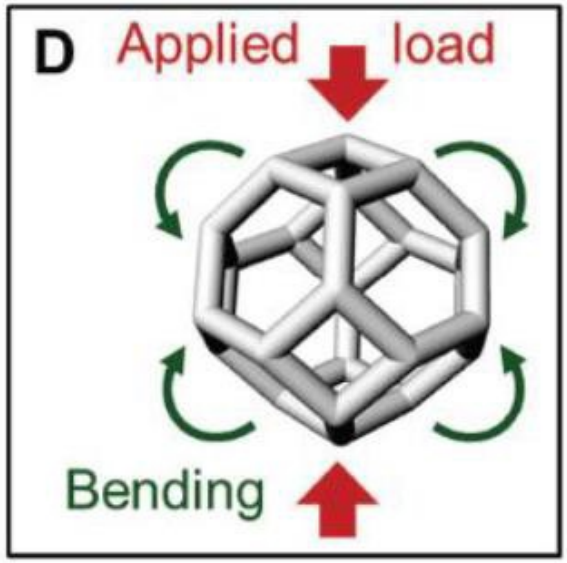
http://www.ems.psu.edu/~green/Opencell.jpg

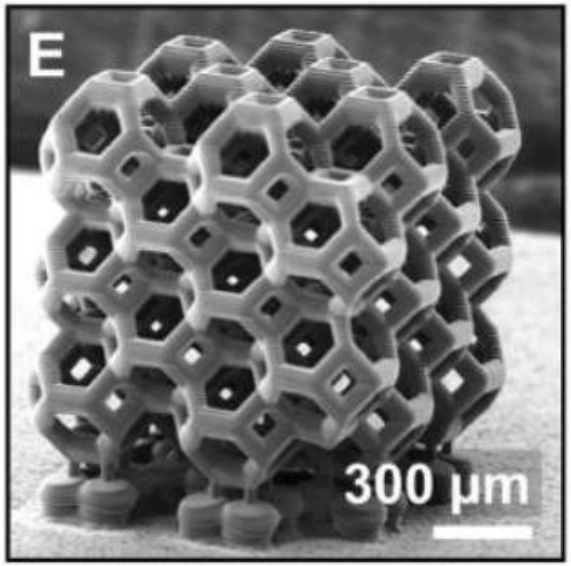
$$Vol_{\text{Foam}} = Vol_{\text{Solid}} + Vol_{\text{Pores}}$$

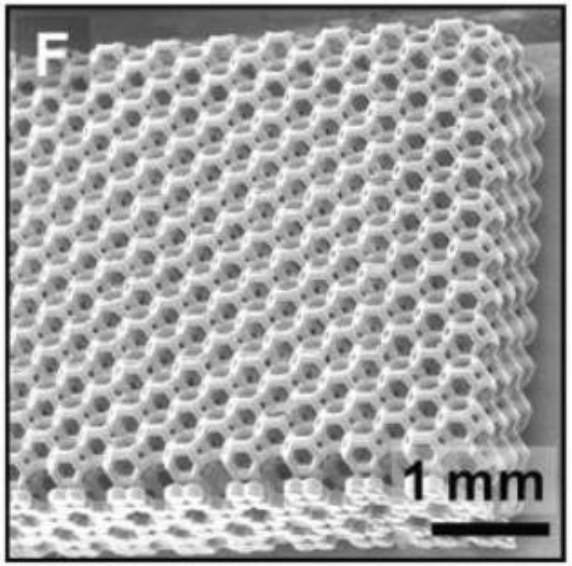
$$\rho_{rel} = \frac{\rho}{\rho_s} = \frac{m/Vol_{\text{Foam}}}{m/Vol_{\text{Solid}}} = \frac{Vol_{\text{Solid}}}{Vol_{\text{Foam}}} =$$

$$= \frac{Vol_{\text{Foam}} - Vol_{\text{Pores}}}{Vol_{\text{Foam}}} = 1 - \frac{Vol_{\text{Pores}}}{Vol_{\text{Foam}}} = 1 - P$$

$$\frac{E}{E_s} \approx (1-P)^2 = \left(\frac{\rho}{\rho_s}\right)^2$$



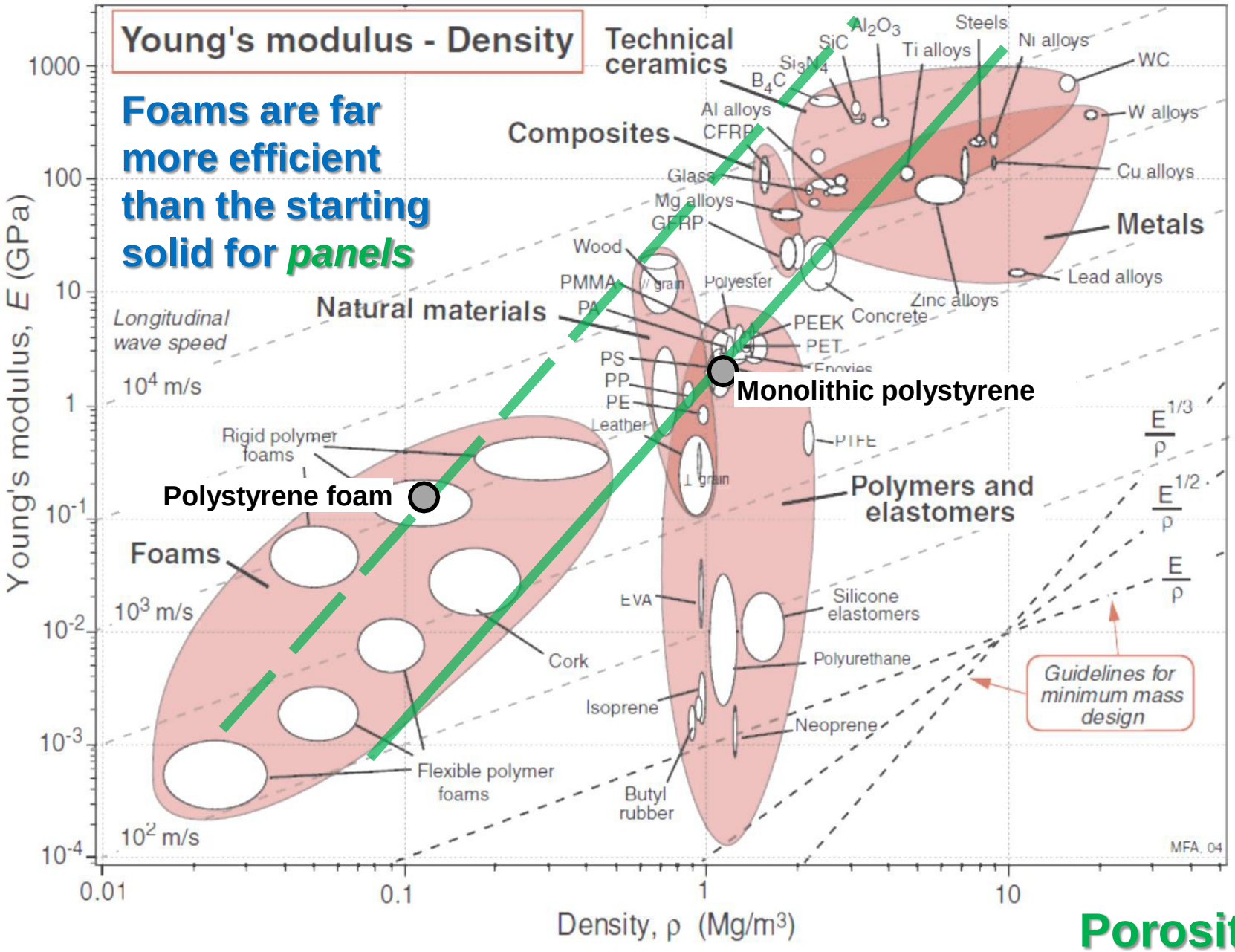




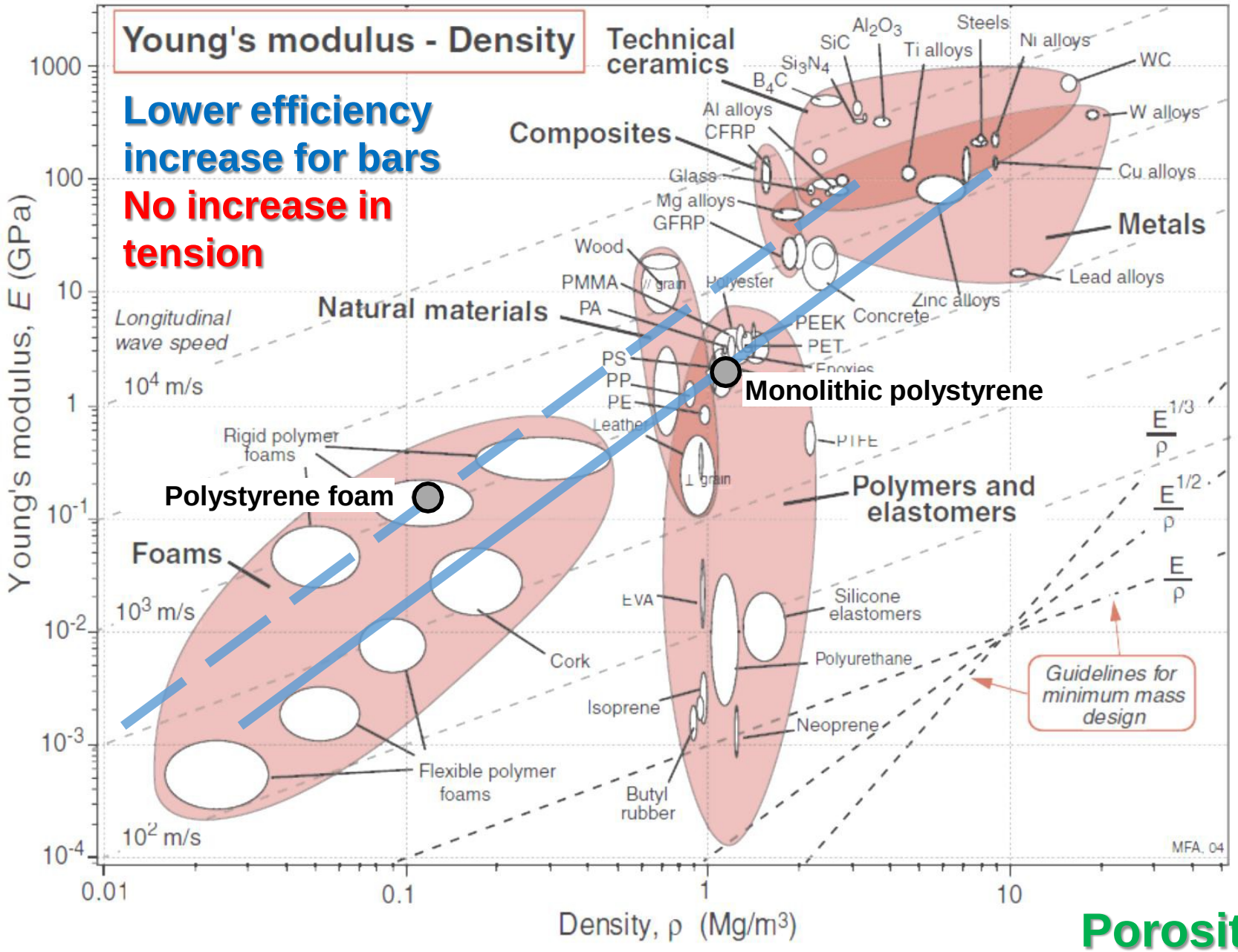
$$\frac{E}{E_S} \approx (1-P)^2 = \left(\frac{\rho}{\rho_S}\right)^2$$

«Standard» foams

Mechanical behavior depending on the bending of edges



Porosity shape factor to be evaluated



Porosity shape factor to be evaluated

Panels

$$I = \frac{E^{1/3}}{\rho} \approx \frac{\left(E_s \cdot \left(\frac{\rho}{\rho_S} \right)^2 \right)^{1/3}}{\rho} = \frac{E_s^{1/3}}{\rho} \cdot \frac{\rho^{2/3}}{\rho_S^{2/3}}$$

Index for the foam

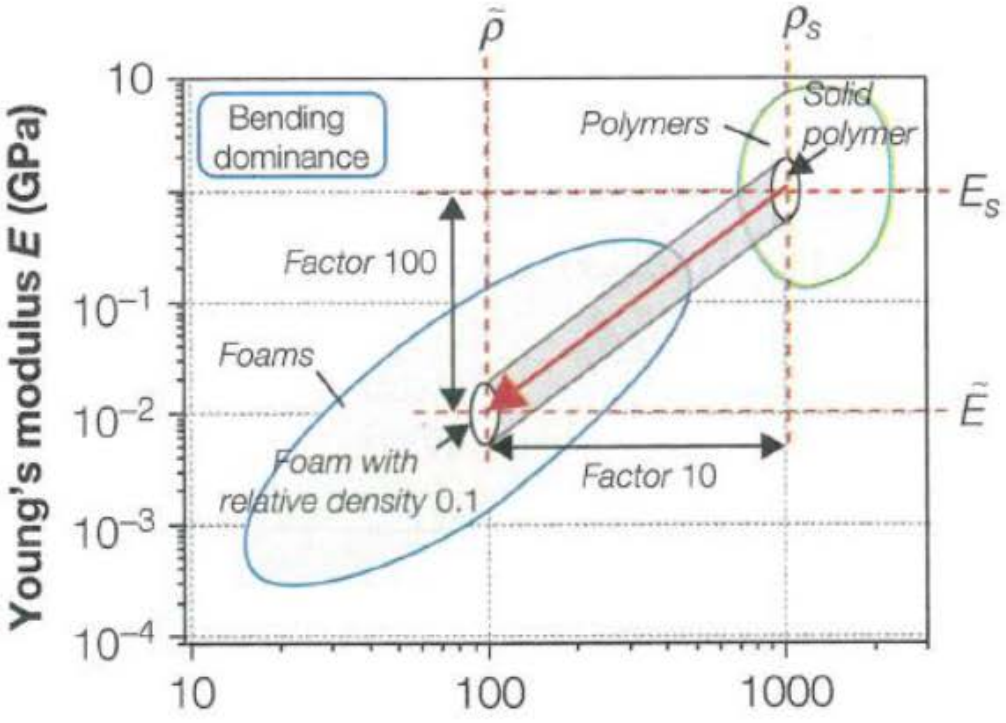
$$= \frac{E_s^{1/3}}{\rho_S^{2/3}} \cdot \frac{1}{\rho^{1/3}} = \frac{E_s^{1/3}}{\rho_S} \cdot \frac{\rho_S^{1/3}}{\rho^{1/3}} =$$

Index for the solid

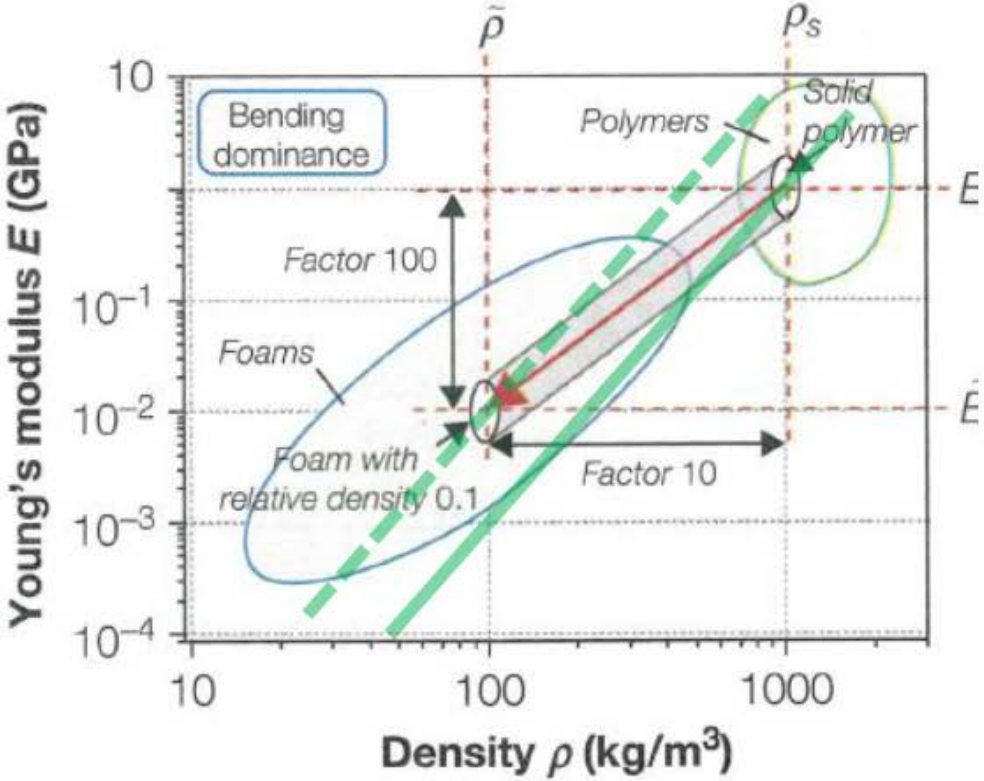
$$= \frac{E_s^{1/3}}{\rho_S} \cdot \frac{1}{[1-P]^{1/3}} = I_S \cdot \frac{1}{[1-P]^{1/3}}$$

Improvement function (of porosity)

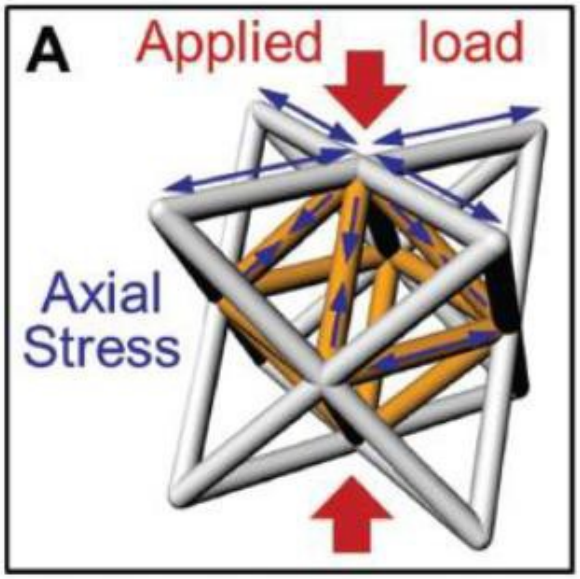
For P=0.9 (90%), the improvement function exceeds 2

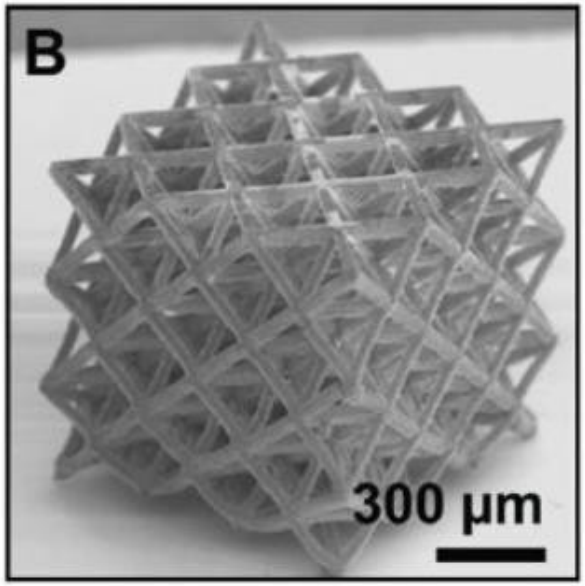


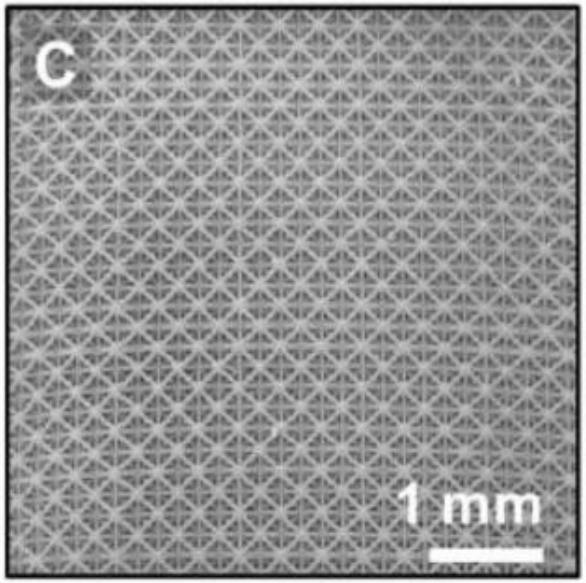
$$\frac{E}{E_s} \approx (1-P)^2 = \left(\frac{\rho}{\rho_s}\right)^2$$



$$I = \frac{E^{1/3}}{\rho} \approx I_s \cdot \frac{1}{[1-P]^{1/3}}$$







New foams

~~$\frac{E}{E_S} \approx (1-P)^2 = \left(\frac{\rho}{\rho_S}\right)^2$~~

Microtruss foams

Mechanical behaviour conditioned by tension and compression of beams

New constitutive equations

$$\frac{E}{E_S} \approx (1-P) = \left(\frac{\rho}{\rho_S}\right)$$

[industrially feasible by adoption of modern additive manufacturing techniques (also known as «3D-printing»)]

New Panels

$$I = \frac{E^{1/3}}{\rho} \approx \frac{\left(E_s \cdot \left(\frac{\rho}{\rho_S}\right)\right)^{1/3}}{\rho} = \frac{E_s^{1/3}}{\rho} \cdot \frac{\rho^{1/3}}{\rho_S^{1/3}}$$

Index for the foam

$$= \frac{E_s^{1/3}}{\rho_S^{1/3}} \cdot \frac{1}{\rho^{2/3}} = \frac{E_s^{1/3}}{\rho_S} \cdot \frac{\rho_S^{2/3}}{\rho^{2/3}}$$

Index for the solid

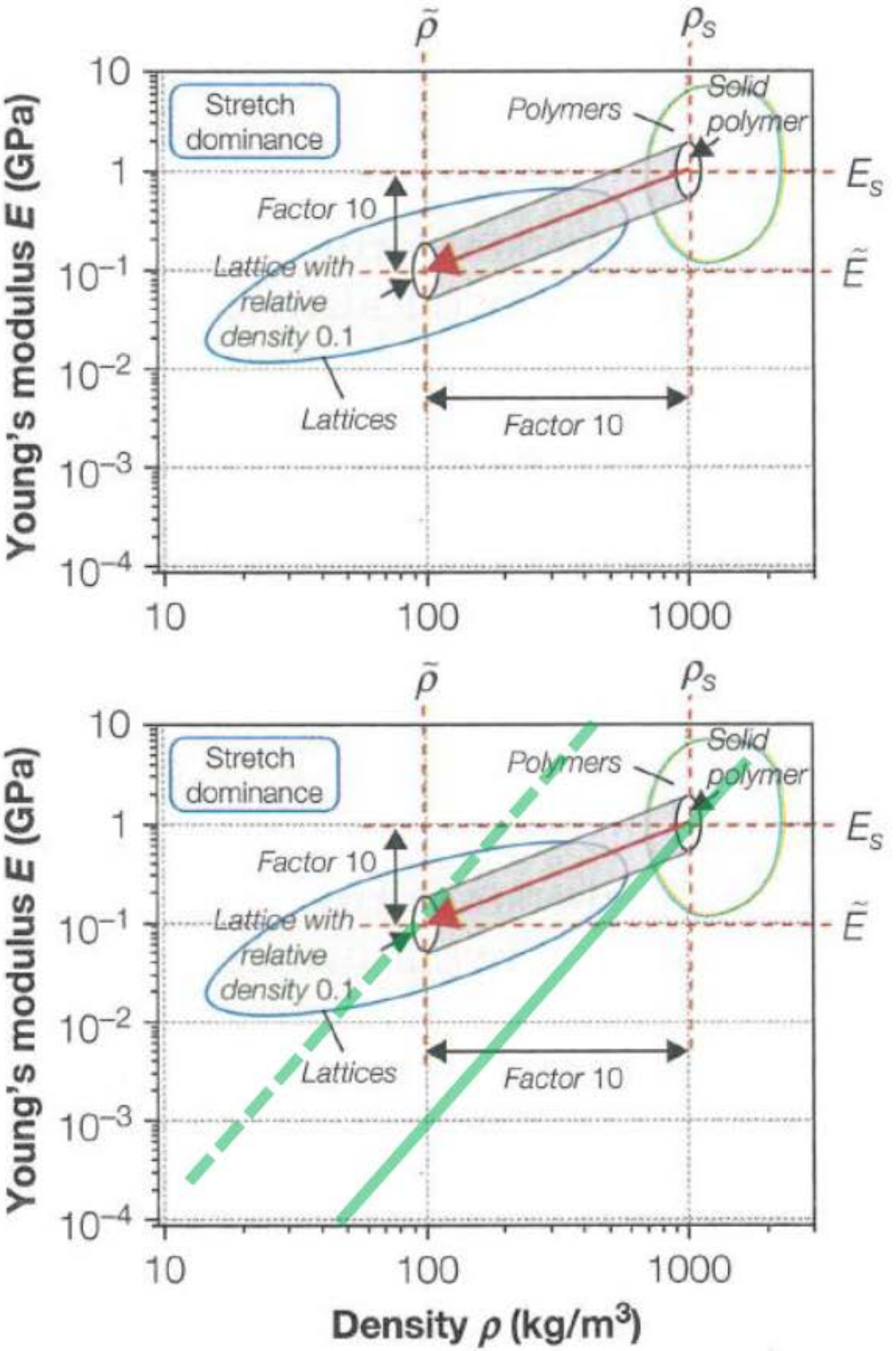
$$= \frac{E_s^{1/3}}{\rho_S} \cdot \left(\frac{1}{1-P}\right)^{2/3} = I_S \cdot \left(\frac{1}{1-P}\right)^{2/3}$$

Improvement function (of porosity)

For P=0.9 (90%), the improvement function exceeds 4.5

$$\frac{E}{E_S} \approx (1-P) = \left(\frac{\rho}{\rho_S}\right)$$

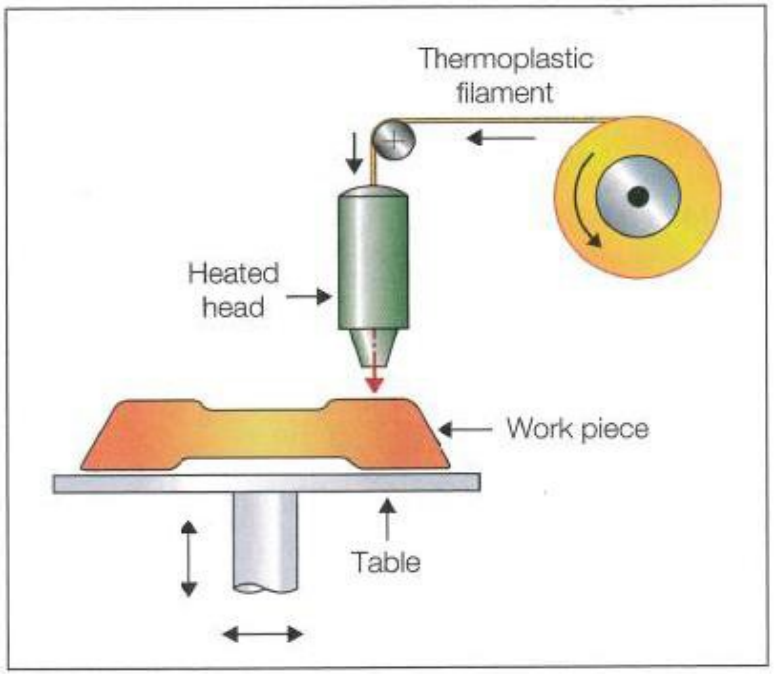
$$I = \frac{E^{1/3}}{\rho} \approx I_S \cdot \left(\frac{1}{1-P}\right)^{2/3}$$



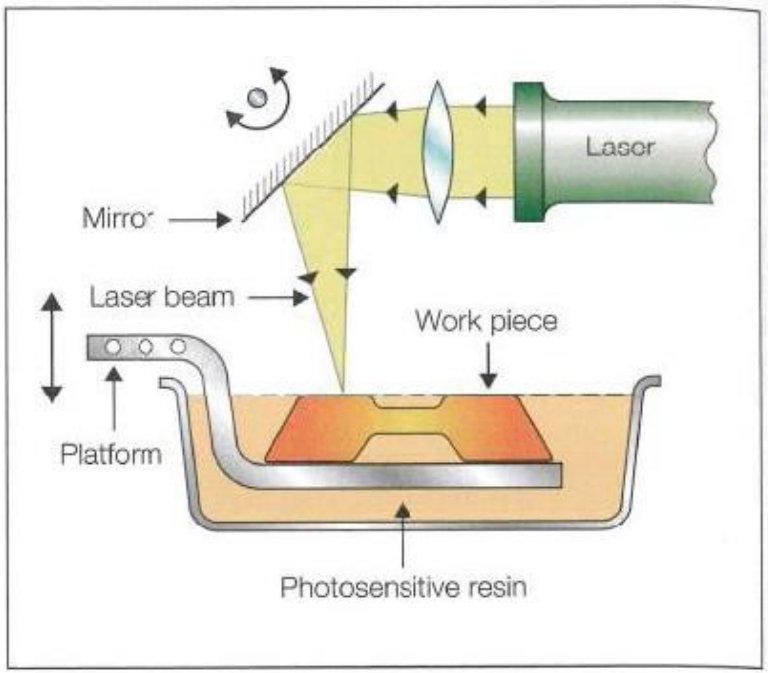
Examples of «3D-printing» technologies

Fundamentaly synergy between process&shape for new materials

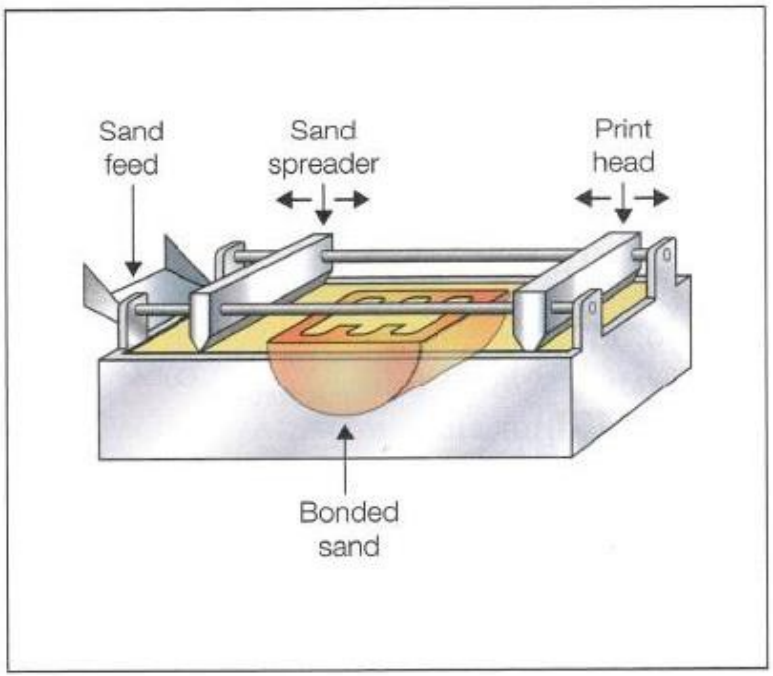
Design of shape
Design of manufacturing devices



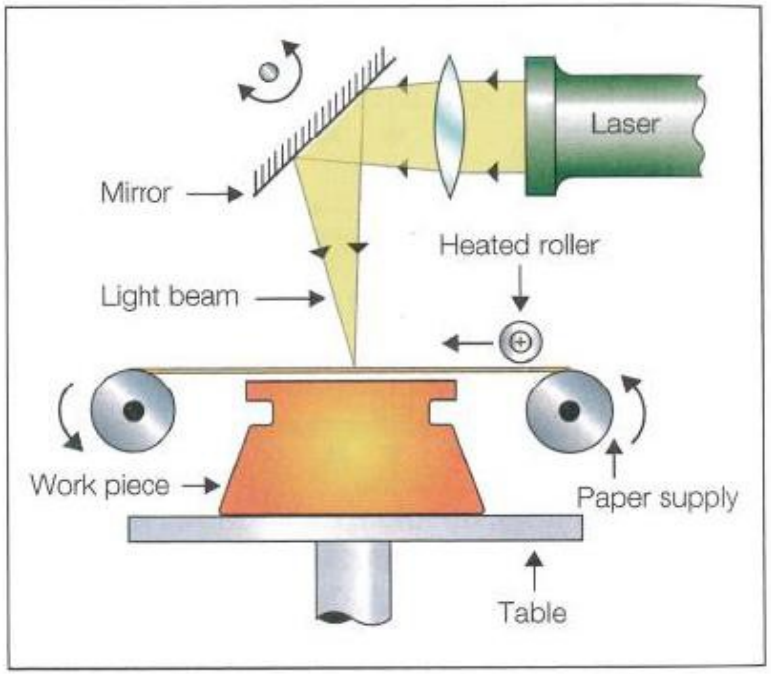
Deposition modeling



Stero-lithography (SLA)



Direct mold modeling



Laminated object manufacture (LOM)

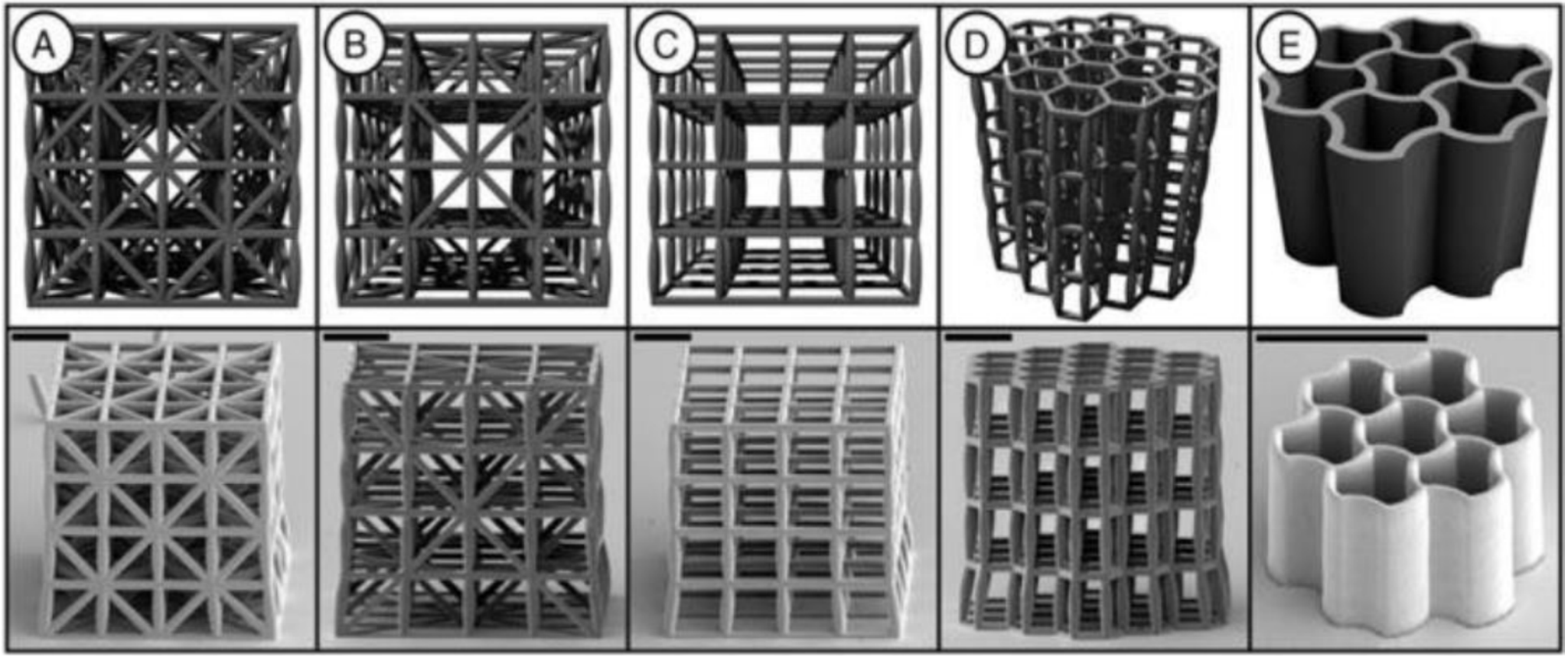
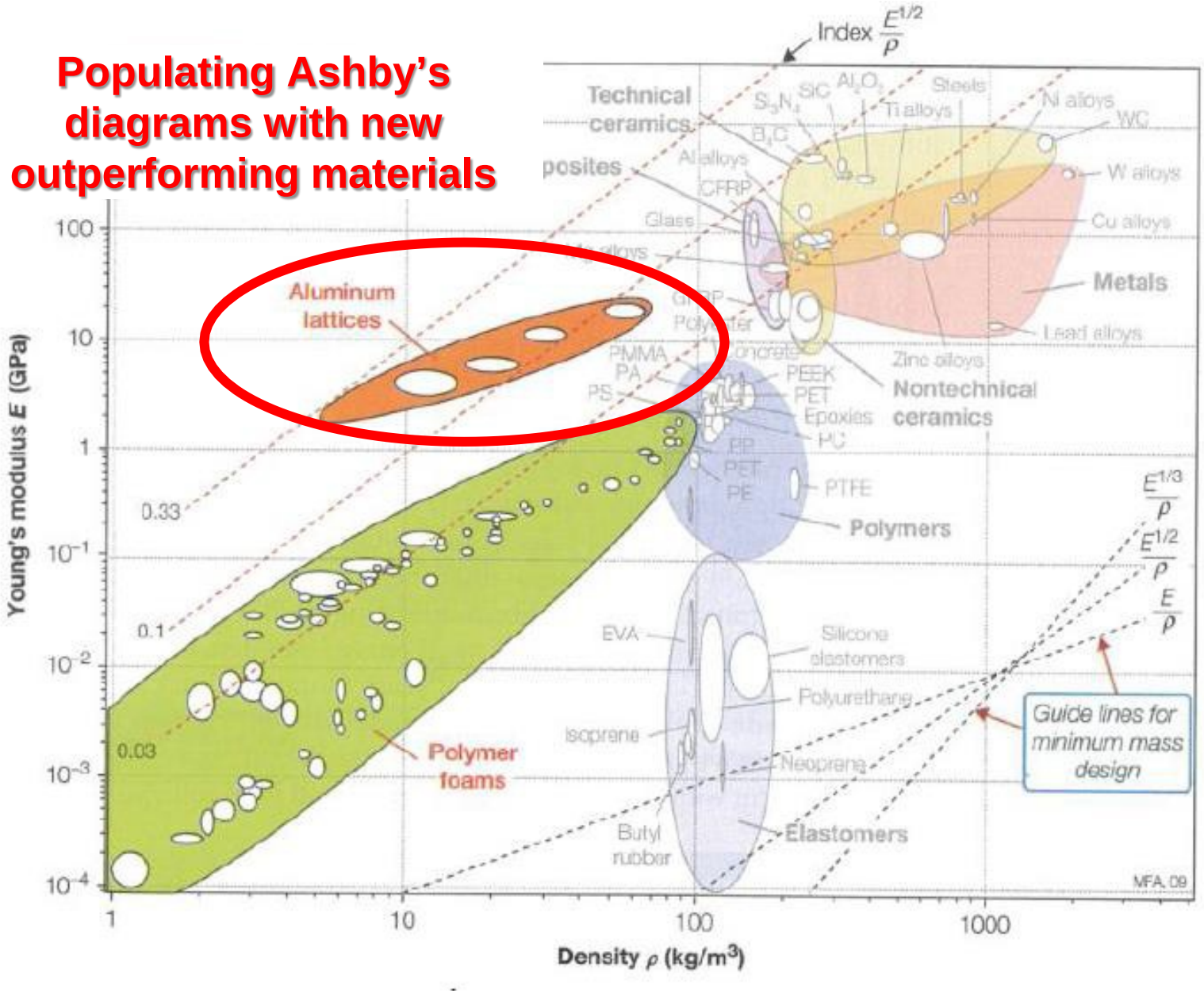
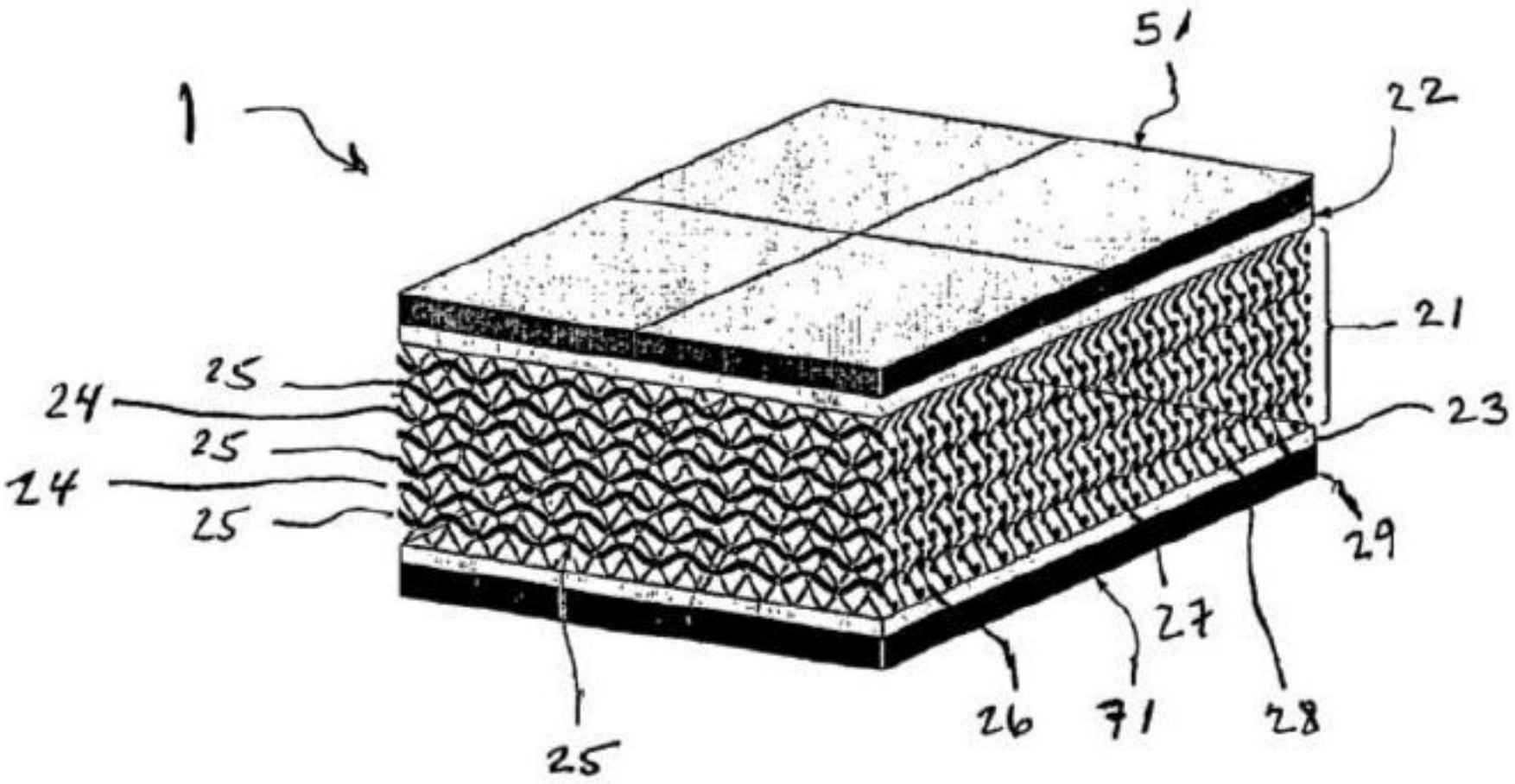


Fig. 1. Computer-aided design models (*Upper*) and SEM images (*Lower*) of examined cellular microarchitectures (scale bars: 10 μm). Design C is an orthotropic construction with nonrigid cubic unit cells (*C*); therefore it generally is considered to behave in a rather bending-dominated manner. We also introduced global diagonal bracings to obtain a more stretching-dominated and collapse-resistant behavior (*B*). When applied to all faces of every unit cell (*A*), the structural stability is enhanced further. Stretching domination is maximized because the structure is fully triangular. The design may be regarded as behaving fairly isotropically. Depending on the stiffness of junctions, collapse mechanisms are less urgent and topologies may be designed so that a maximum of structural elements are arranged in loading direction, without risking early global buckling. We realized that approach with a hexagonal truss structure (*D*), whose unit cell geometry is not rigid, just like that of design C, and with a shape-optimized honeycomb design (*E*). Both constructions behave anisotropically.

[http:I!3dprintingindustry.com/201410210 7l german-scientists-3d-print-lightweight-materia1-stronger-steell]

Populating Ashby's diagrams with new outperforming materials



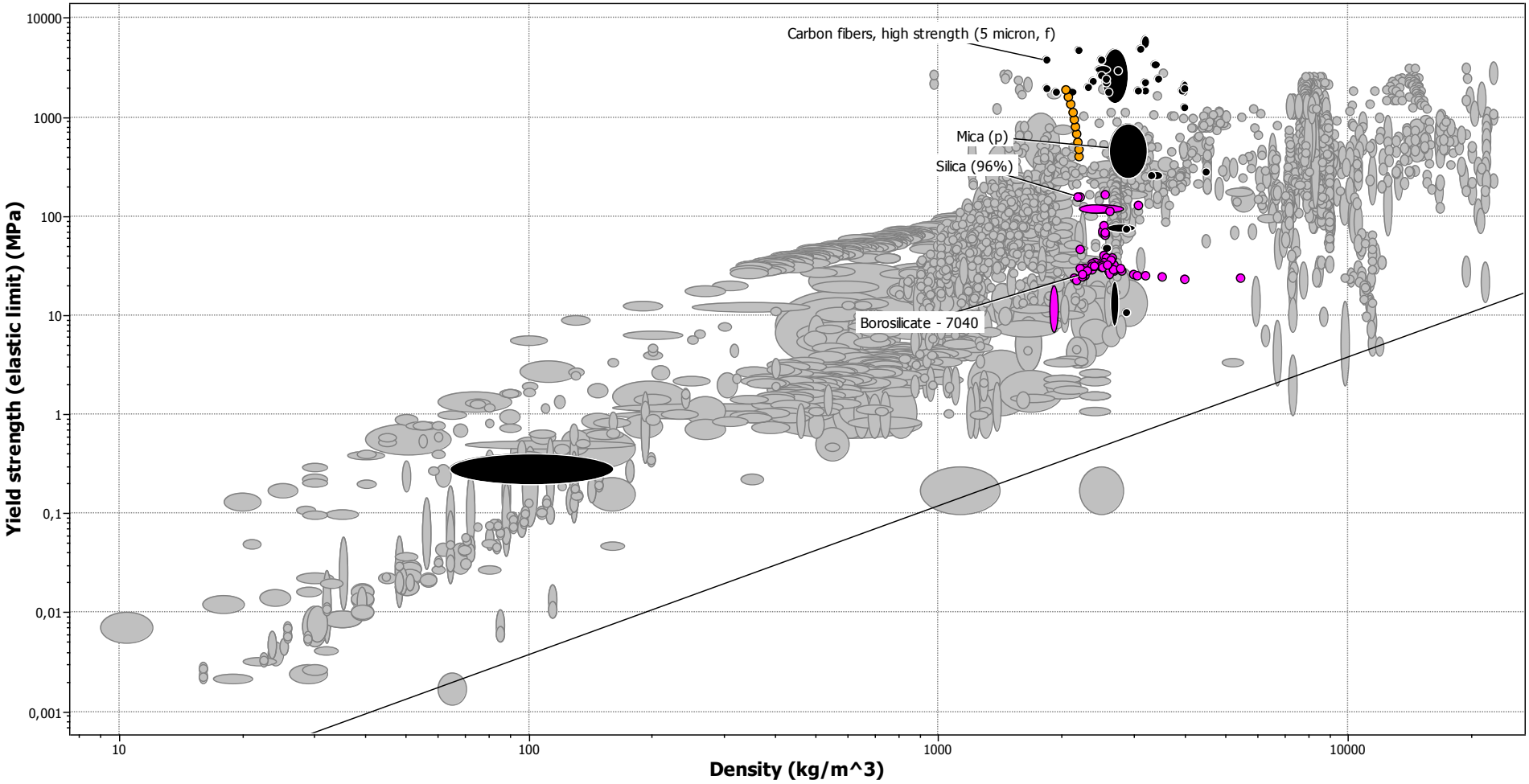


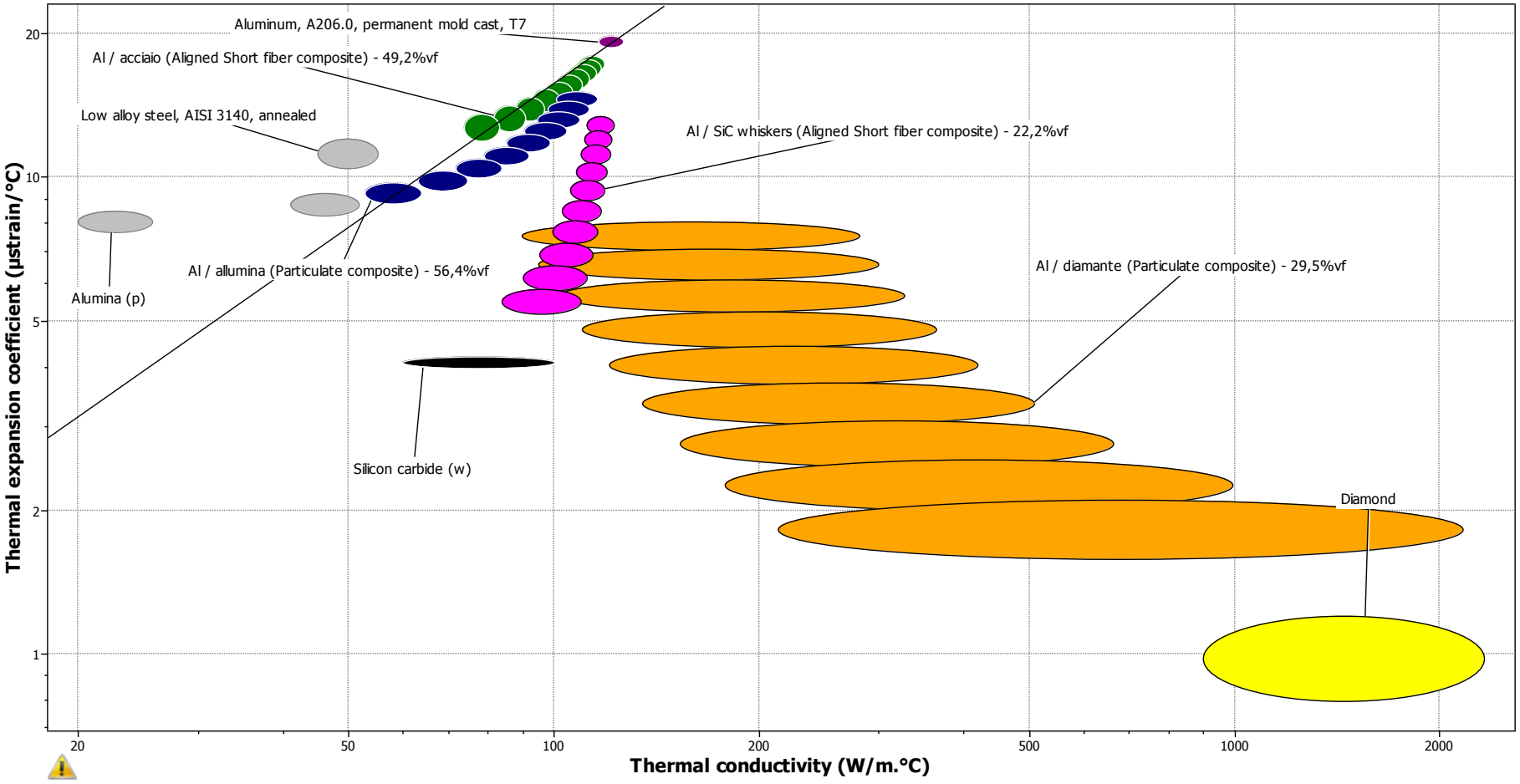
Applications in aerospace sandwich structures
[U.S. Patent US7913611]

Better materials: enhanced material performance indices

Composites may fill the voids
Example: borosilicate + C fibres, for bars subjected to bending

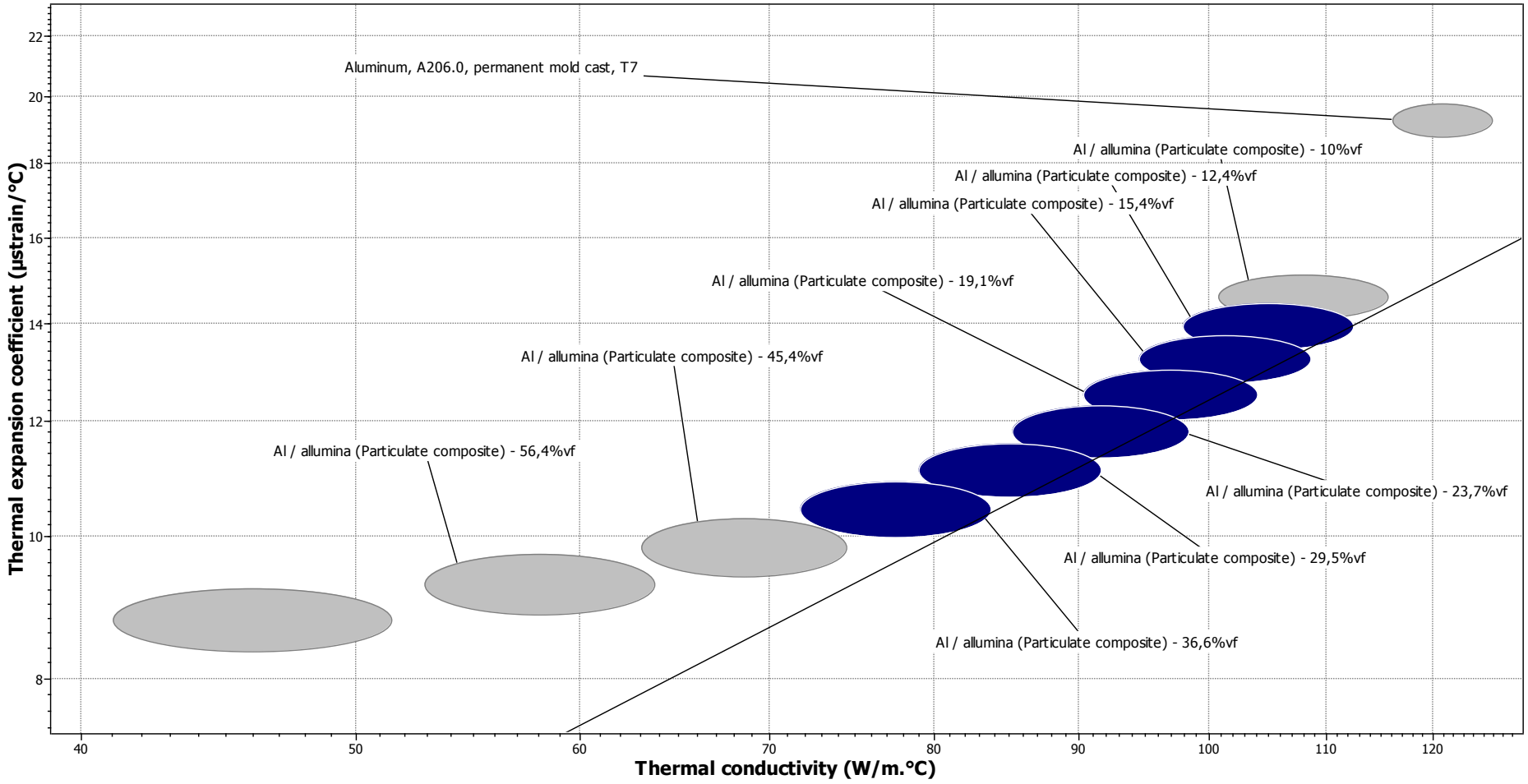
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Sensitivity to thermal distorsion

Possible «reinforcements» of aluminum



Sensitivity to thermal distorsion

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Dramatic improvement even of «poor» foams

Effective filling of intersting voids in materials property charts

