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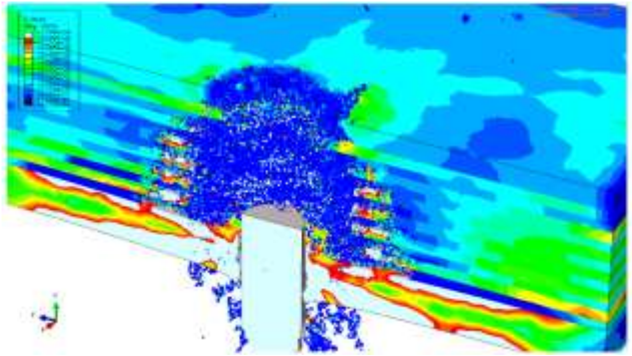

Seuraavan sukupolven Ballistiset Keraamit (BalKer)

16.11.2017 MATINE tutkimusseminaari

Tomi Lindroos, Matti Lindroos

Sisältö

1. Projektin perustiedot
2. Tavoitteet
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4. Tutkimusta ohjaavat kysymykset
5. Tehtävät

Projektin perustiedot

- *Seuraavan sukupolven Ballistiset Keraamit – BalKer*, projektikoodi 2500M-0075
- Projekti on suunniteltu kaksivuotiseksi alkaen 1.1.2017 ja päättyen 31.11.2018.
- Rahoitus 2017: MATINE 58 700 €, VTT 17732 €, **76432 €**
- Ohjausryhmä:
    - Tomi Lindroos, VTT
    - Ilkka Laine, (Paavo Raerinne), PVTUTKL
    - Jukka Kemppainen, Exote Oy
    - Pekka Lintula, Nammo Lapua Oy

TAVOITTEET

- Projektin kokonaistavoitteena on kehittää työkaluja ja menetelmiä seuraavan sukupolven ballistisen keraamin kehittämiseksi mahdollistaen suorituskyvyn (suojaustaso / neliöpaino) kasvattamisen.

- ***Tutkimusta ohjaa hypoteesi: Kaksifaasinen lamellaarin keraamirakenne jakaa ballistisen iskun energiaa tehokkaammin ja kasvattaa näin ballistista suorituskykyä***

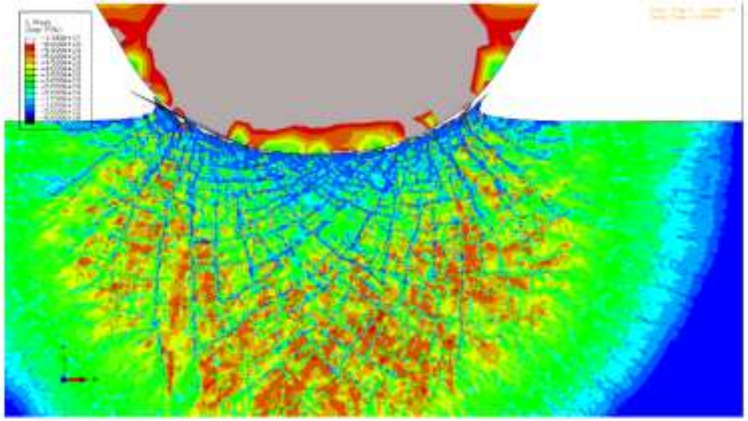
- Kokonaistavoite koostuu seuraavista osatavoitteista
  - Mallinnusavusteisen materiaalisuunnittelun hyödyntäminen luontoa jäljittelevän rakenteen valmistuksessa. Mallinnuksen avulla määrittää suuntaviivat kokeelliselle tutkimukselle ja näin nopeutta kehitystä.
  - Valmistaa hienojakoisen lamellaarisen mikrorakenteen omaavaa kaksifaasikeraamia reaktiivista kuumapuristusta hyödyntäen
  - Todentaa lamellaarisella rakenteella saavutettava suorituskyvyn kasvu sekä simuloimalla että käytännön ammuntakokein

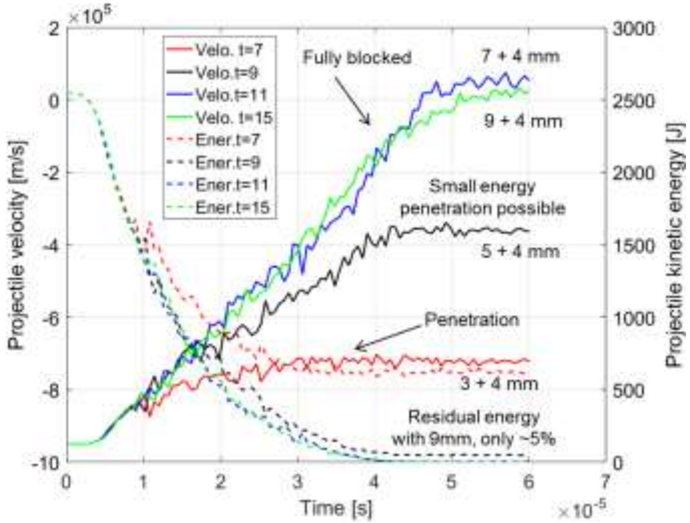
- Tavoiteltava neliöpaino keraamille < 40 kg/m^2, suojaustasolle NIJ STD 0101.06 taso IV. Tämä mahdollistaisi taktisten suojaliivien lisälevyn (ESAPI-levy, L-koko) kohdalla noin 20% keventämisen verrattuna kaupalliseen BAE Systemsin vastaavaan 2,9 kg painoiseen levyyn [1].

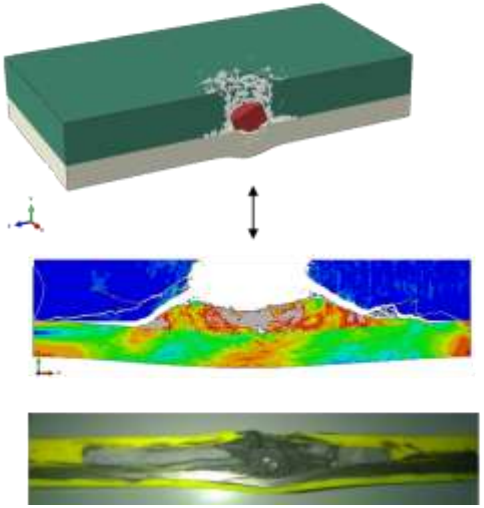
[1] *Hard Body Armor Insert Plates BAE Systems (2008)*

TAUSTA

- 2015-2016 MATINE Balma projektin tulosten hyödyntäminen
- Mallinnusavusteinen materiaalisuunnittelu
  - Synteettiset mikrorakennemallit
  - Makrotason käyttäytyminen





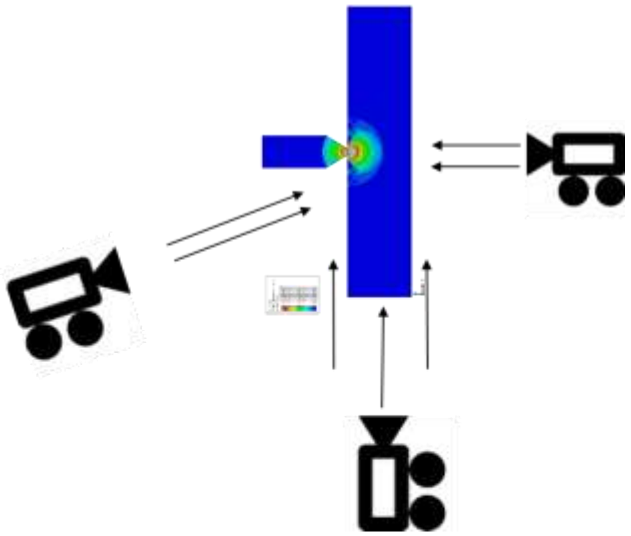


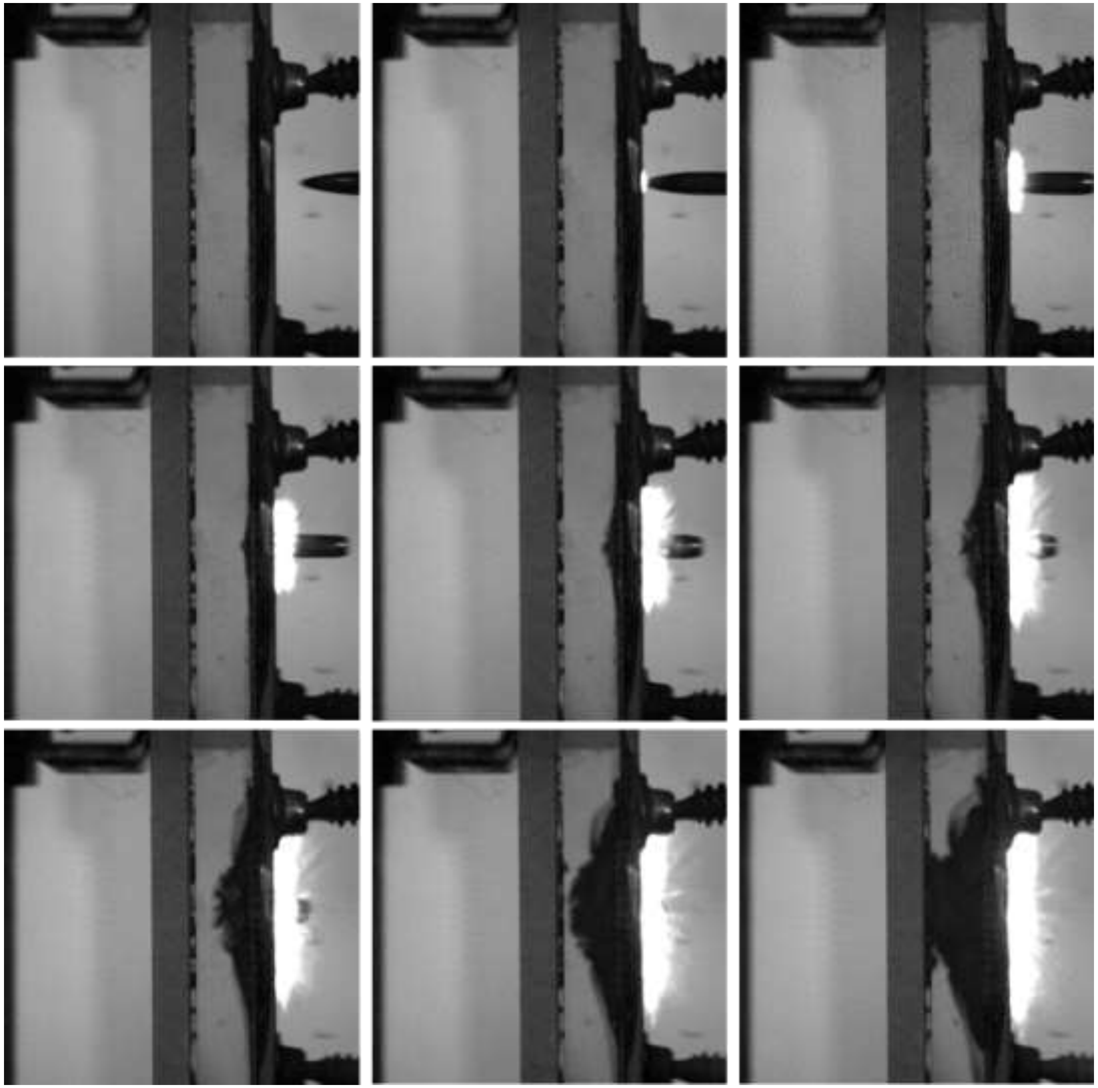
Multiple tests has shown that critical thickness is ~7 mm when packing is correct ➔ ***simulations have good correlation!***

High Speed Camera tests

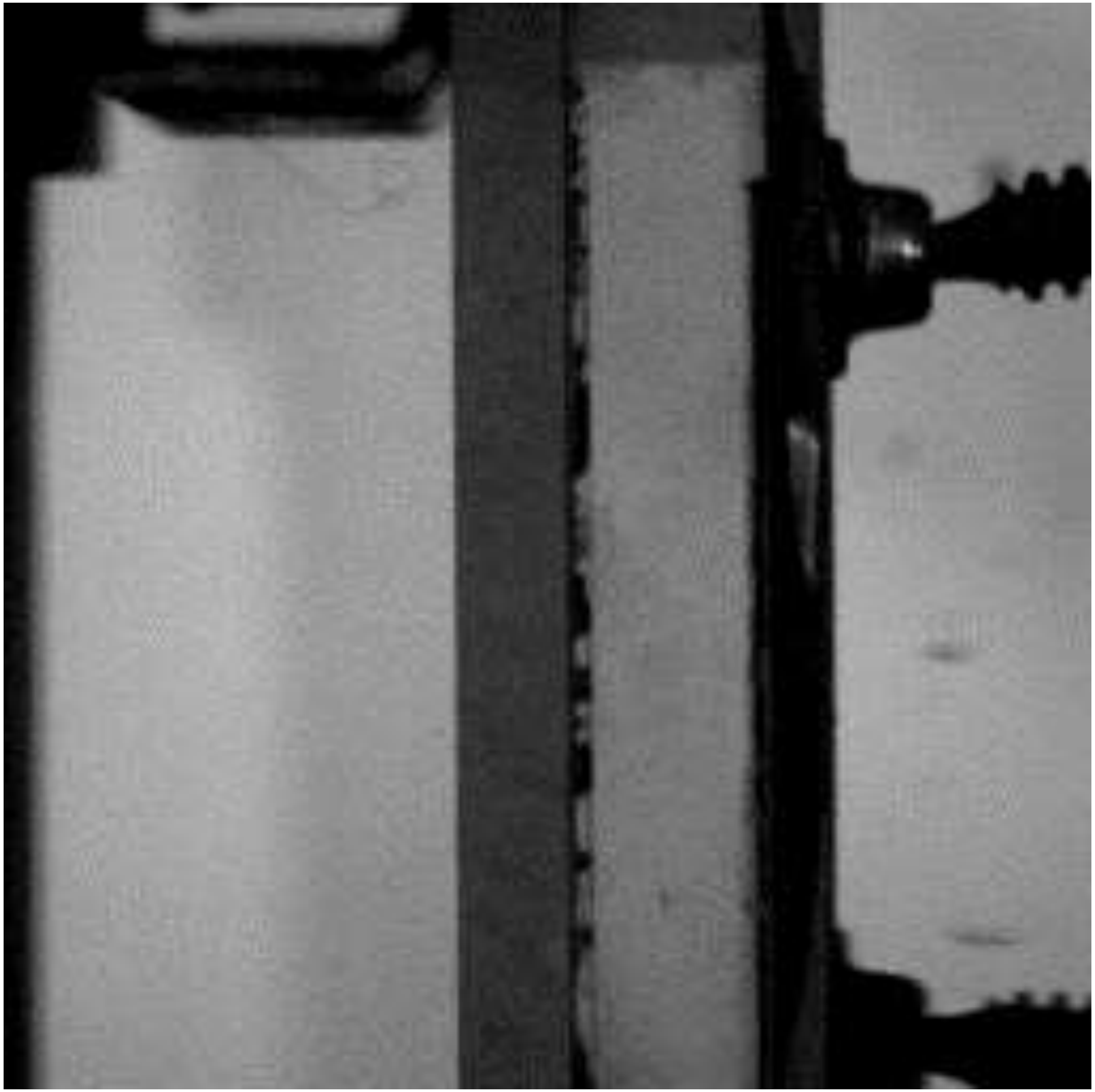
- ***Verification data for models***

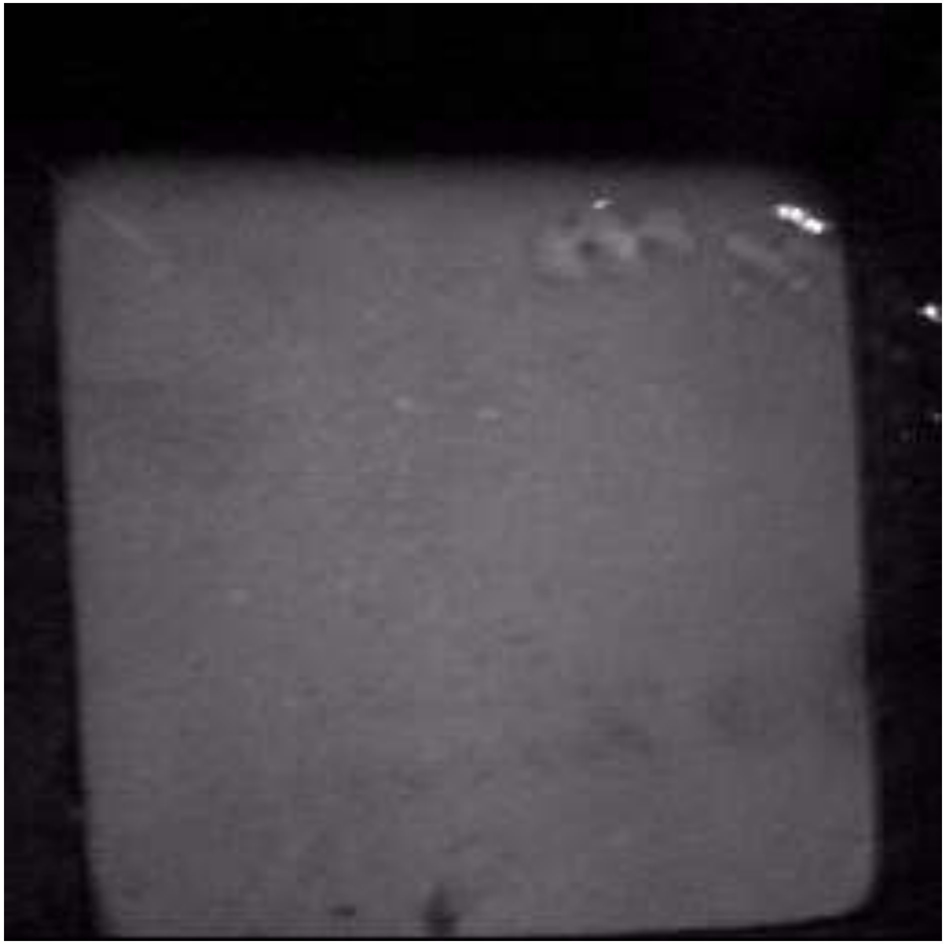
- P80
- Exote 7mm
- Polycarbonate backing
- 200 000 fps

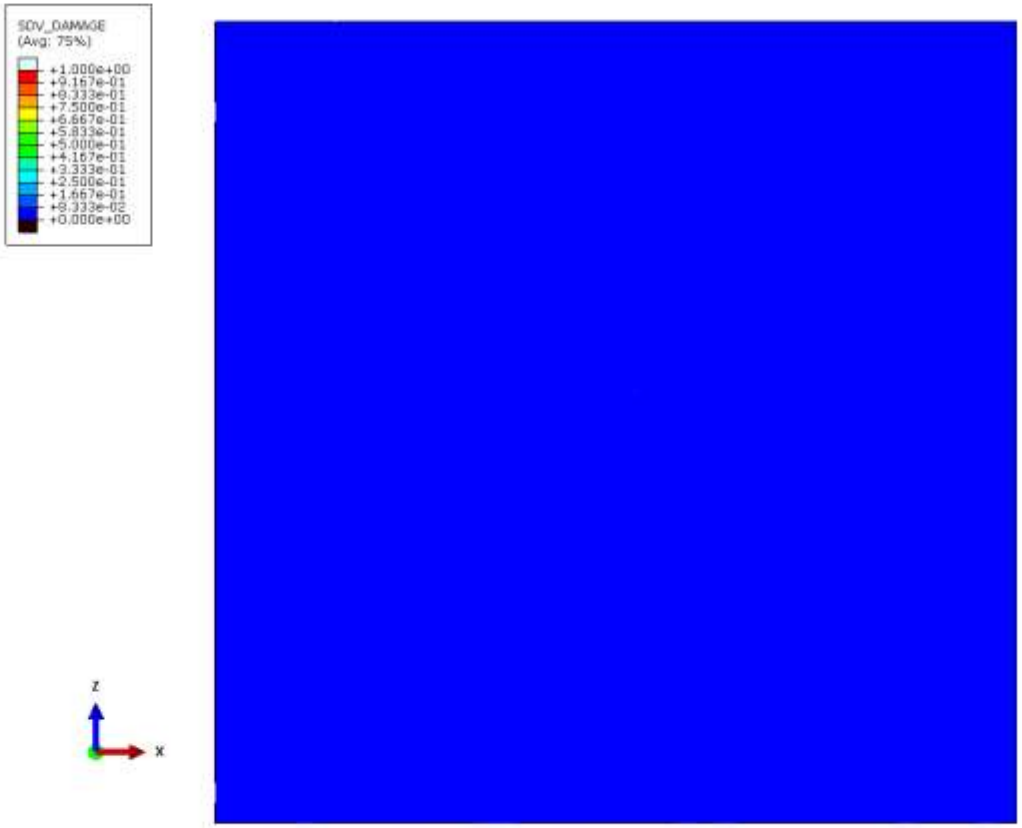




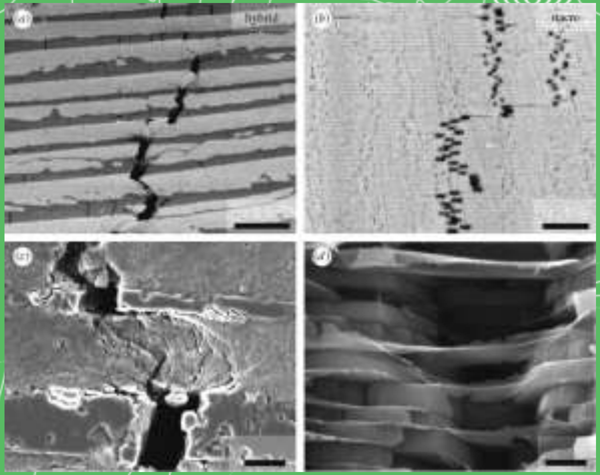
7 mm Exote + PC tausta, P-80





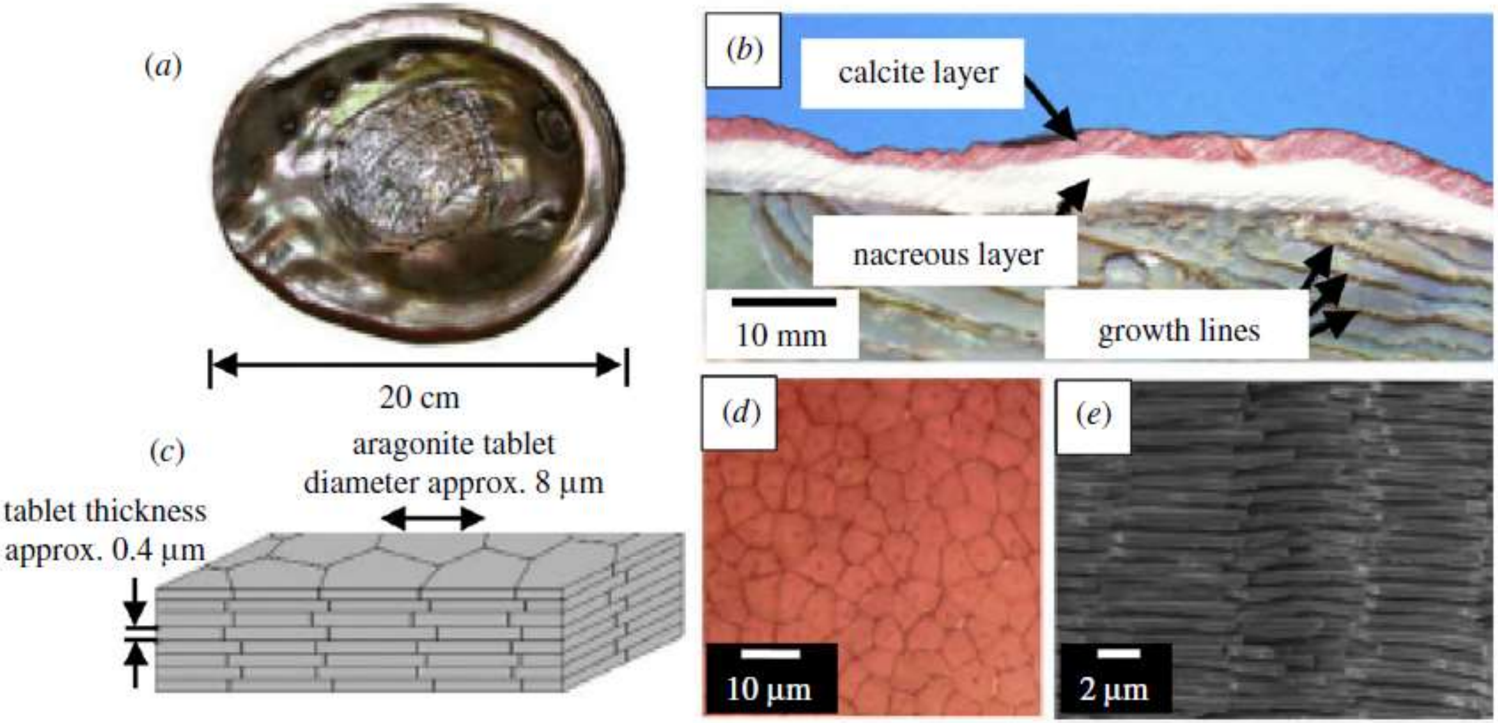

SDV_DAMAGE
(Avg: 75%)
+1.000e+00
+9.167e-01
+8.333e-01
+7.500e-01
+6.667e-01
+5.833e-01
+5.000e-01
+4.167e-01
+3.333e-01
+2.500e-01
+1.667e-01
+8.333e-02
+0.000e+00
z
x

Biomimetic composites



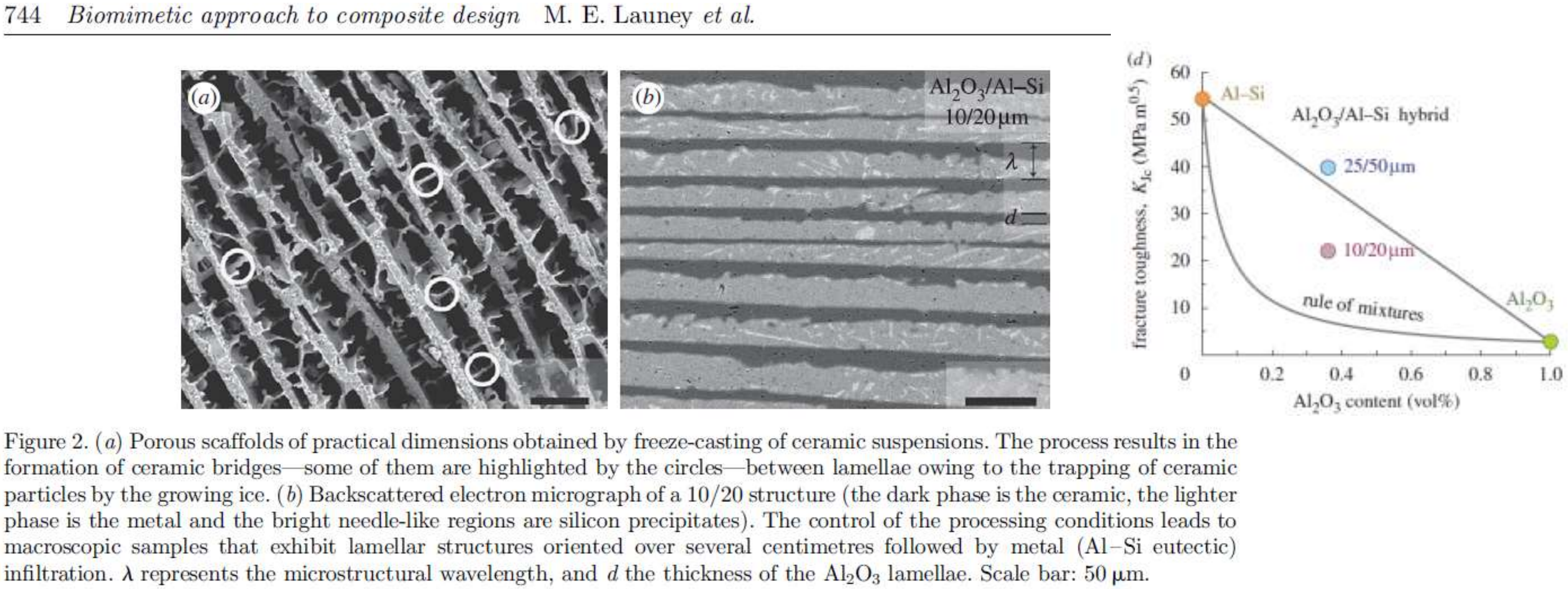
A novel biomimetic approach to the design of high-performance ceramic–metal composites
Maximilien E. Launey,
Published 14 October 2009. DOI: 10.1098/rsif.2009.0331

Biomimetic composites – learning from nature



[1] Biologically inspired crack delocalization in a high strain-rate environment C. Knipprath et.al., J. R. Soc. Interface (2012)

Biomimetic composites



744 *Biomimetic approach to composite design* M. E. Launey *et al.*

Figure 2. (*a*) Porous scaffolds of practical dimensions obtained by freeze-casting of ceramic suspensions. The process results in the formation of ceramic bridges—some of them are highlighted by the circles—between lamellae owing to the trapping of ceramic particles by the growing ice. (*b*) Backscattered electron micrograph of a 10/20 structure (the dark phase is the ceramic, the lighter phase is the metal and the bright needle-like regions are silicon precipitates). The control of the processing conditions leads to macroscopic samples that exhibit lamellar structures oriented over several centimetres followed by metal (Al–Si eutectic) infiltration. λ represents the microstructural wavelength, and *d* the thickness of the Al_2O_3 lamellae. Scale bar: 50 µm.

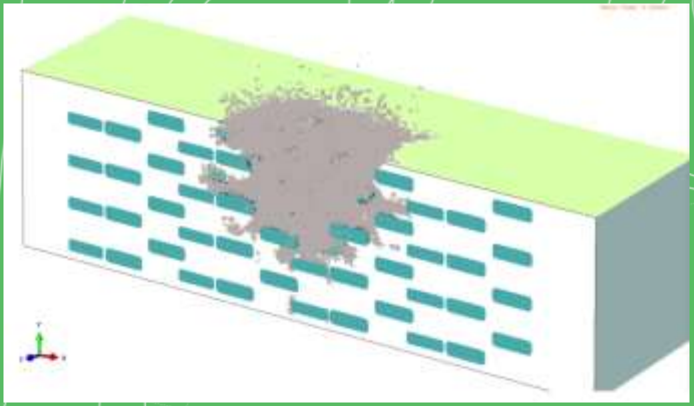
Tehtävät 2017

Synteettiset mikrorakennemallit

- Luodaan synteettisiä B_4C-Al_2O_3 mikrorakennemalleja joiden avulla tutkitaan faasiosuuksien, kokojakauman ja muodon vaikutusta materiaalin käyttäytymiseen ballistisessa iskussa

Kaksifaasikeraamit ja reaktiivinen kuumapuristus

- Ensisijainen koostumus $B_2O_3 + SiO_2 + Al + C \Rightarrow (B, Si)_4C + Al_2O_3$
- Materiaalikoostumuksen ja reaktiokinetiikan säätö, peruslähtöaineiden (B_2O_3, Al, C) suhteiden säätö, sekä mahdolliset lisäaineen (SiO_2, Mg, B)

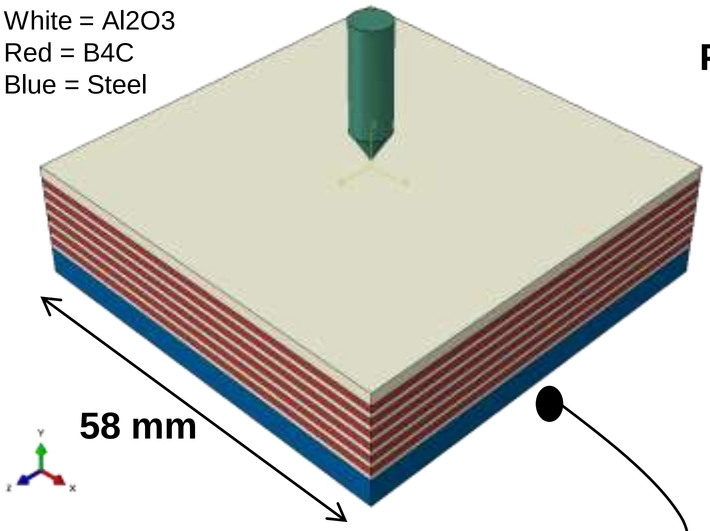


Synteettiset mikrorakennemallit

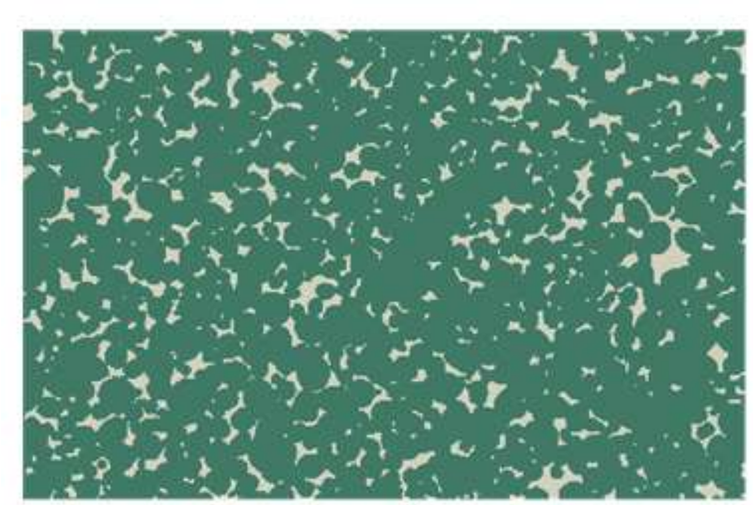
Model description – 3 stage modeling concept

Macroscopic model

White = Al2O3
Red = B4C
Blue = Steel



PERFORMANCE

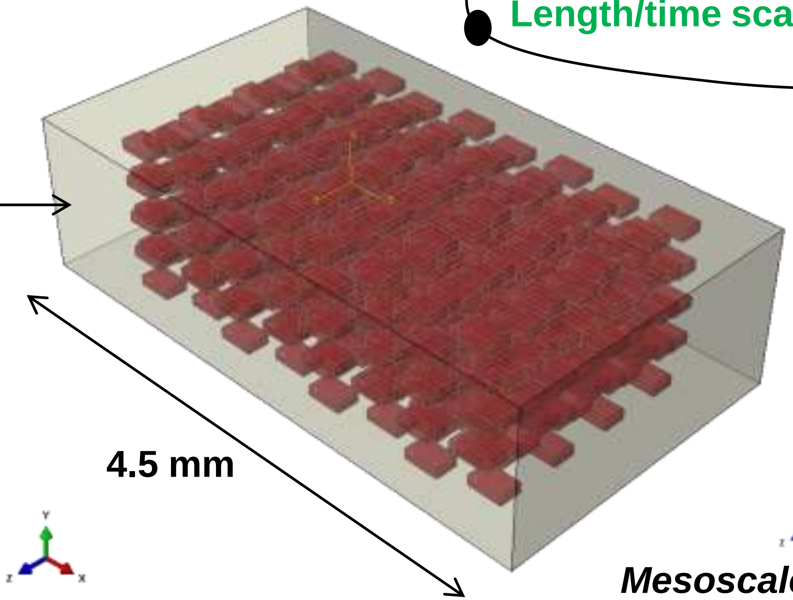


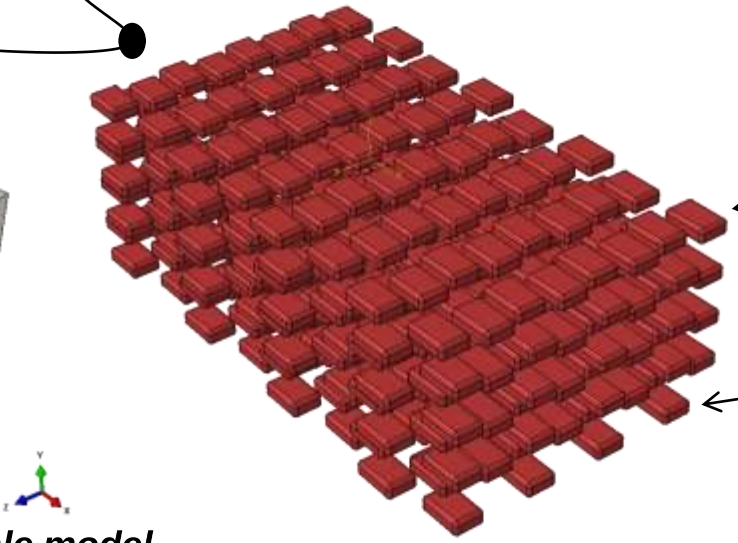
Microstructure model (Exote)

E.g., 100-1000 um (for current material)

Length/time scale

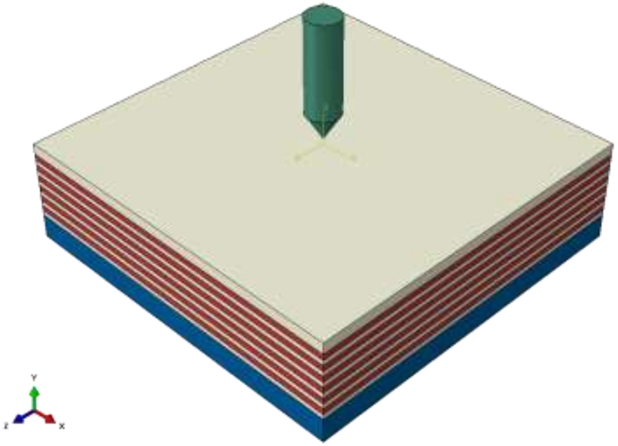
Matrix
aluminium
oxide

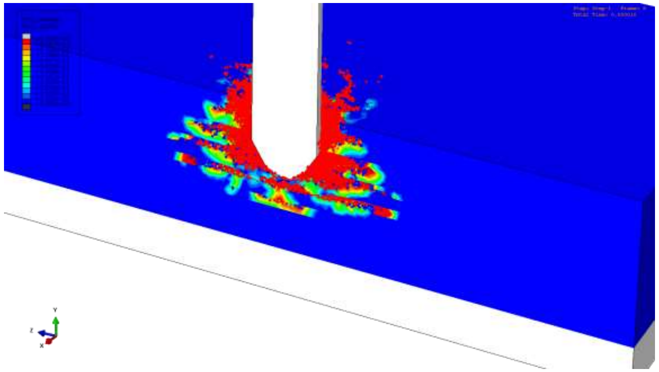




Mesoscale model

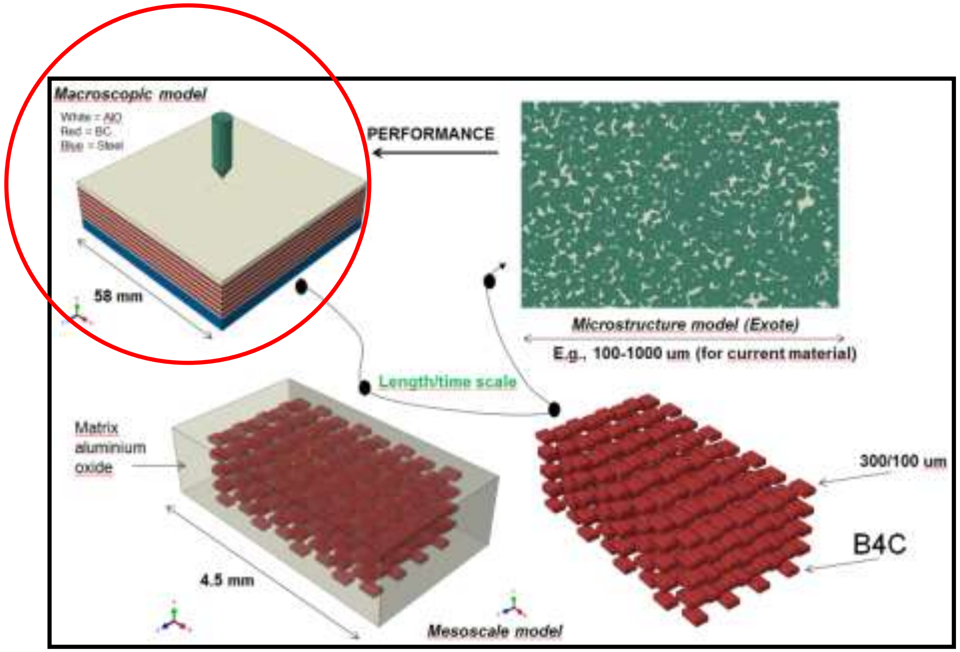
Macroscopic modeling



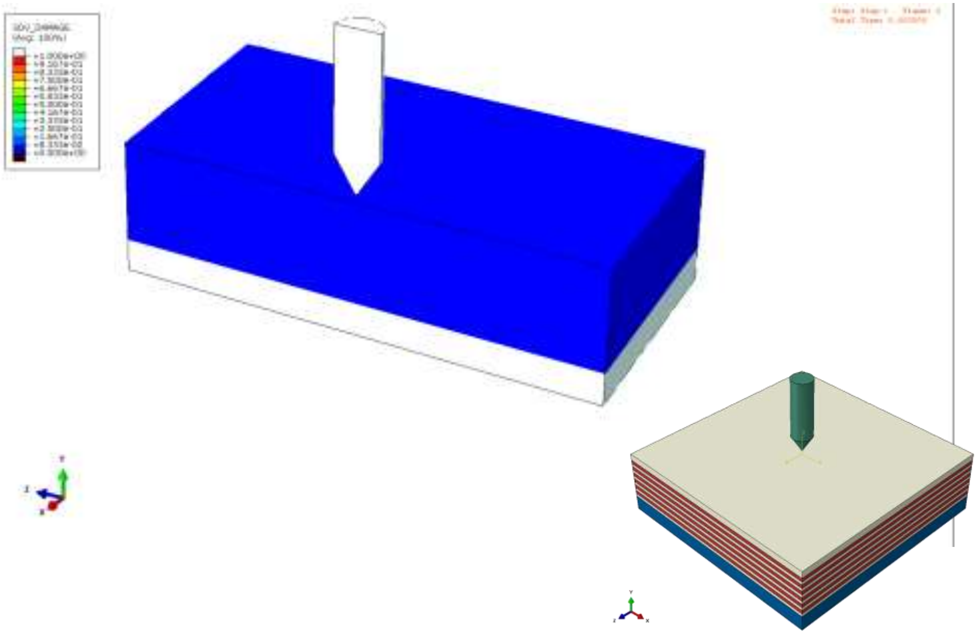


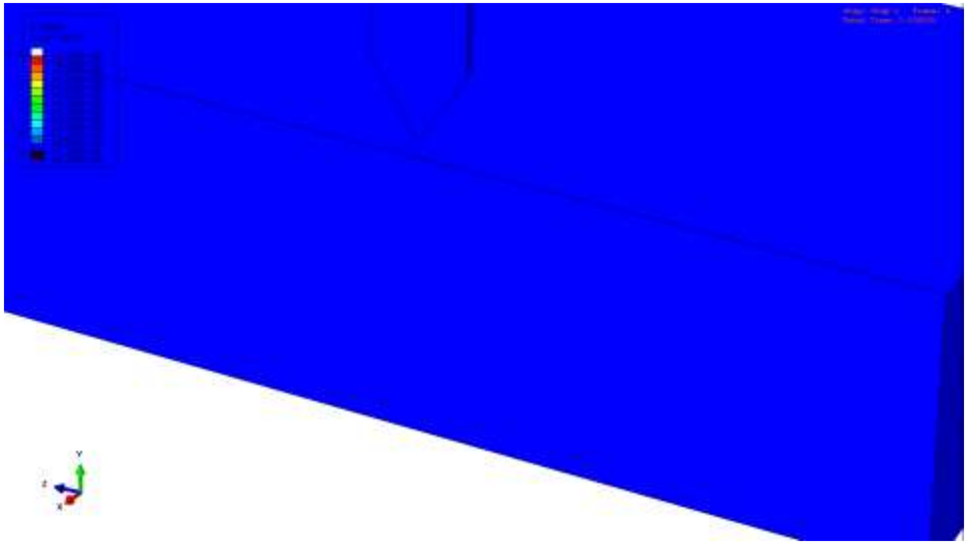
Possibilities

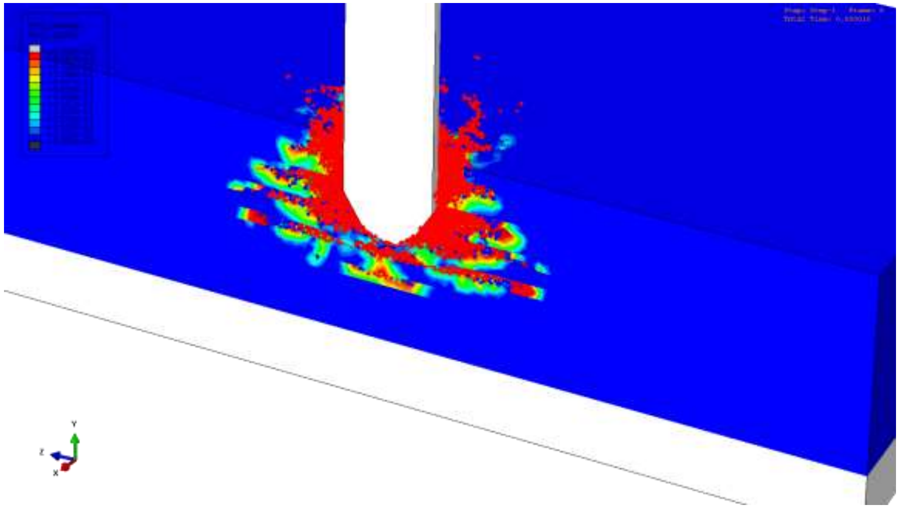
- Material solution performance in large scale
- Case-studies, e.g.,
  - Impact angle
  - Impact velocity
  - Projectile material
  - Lightweight vs. ballistic resistance

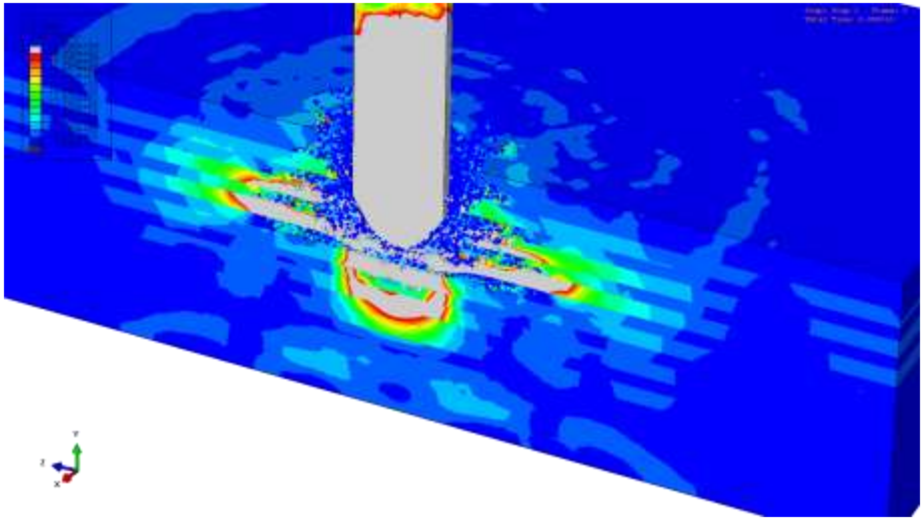


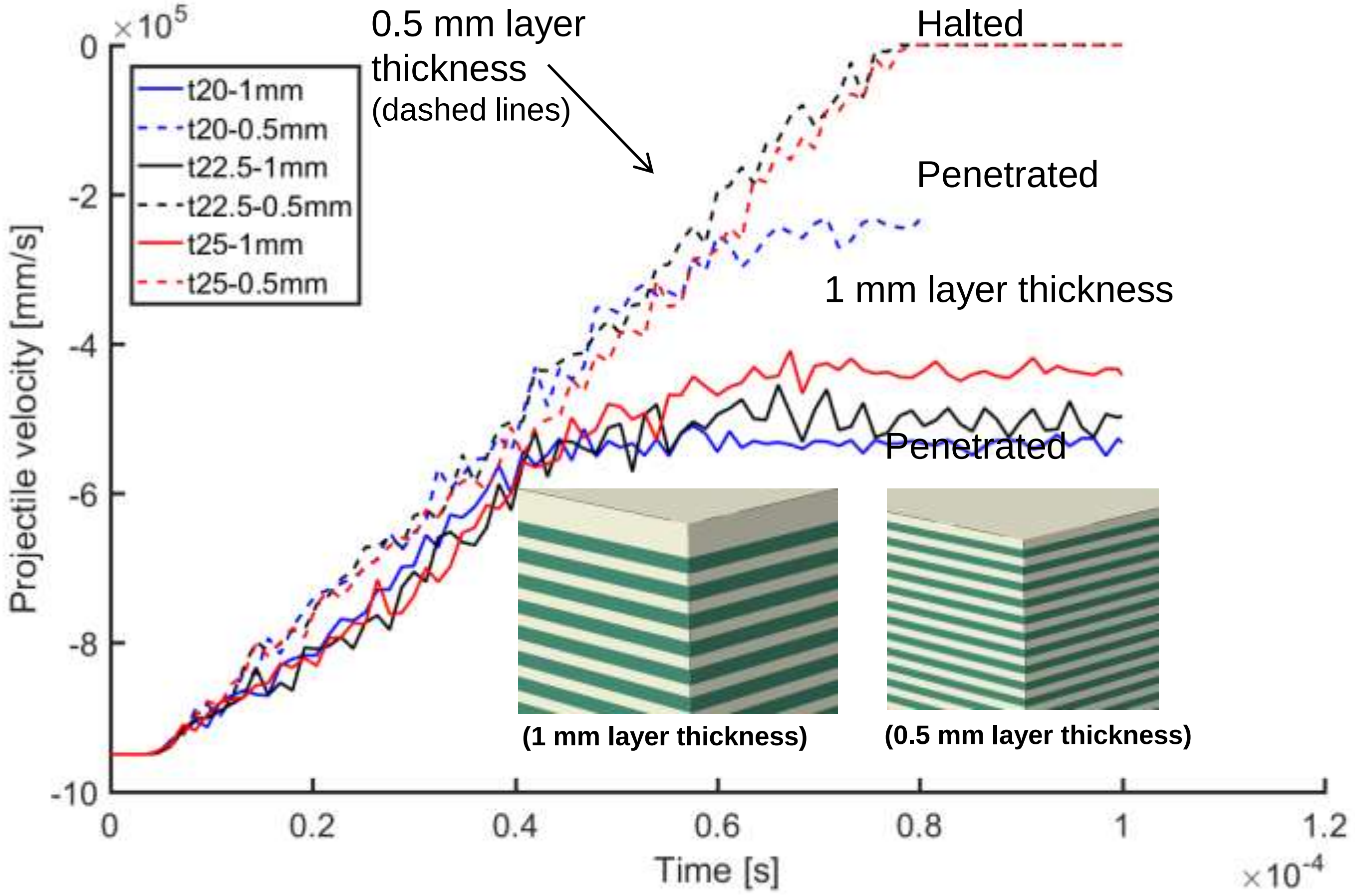
Macroscale model

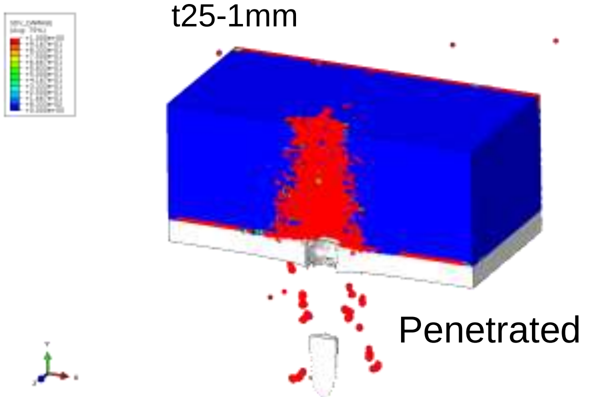


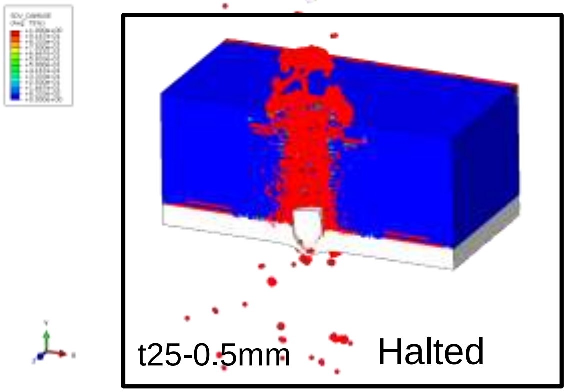


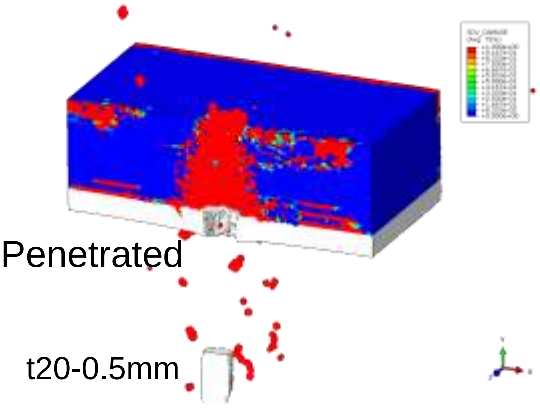


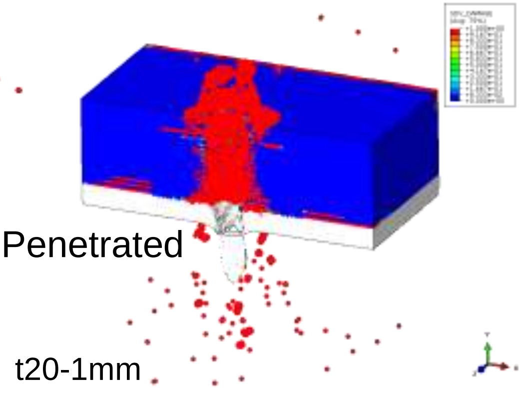


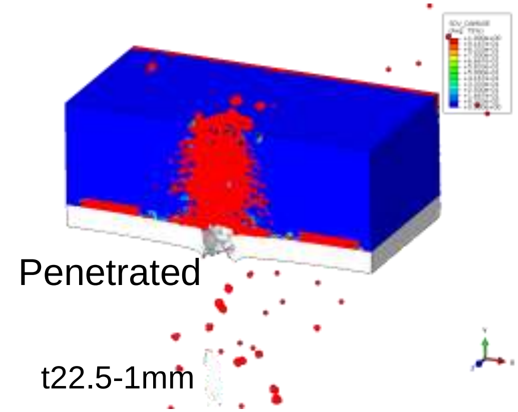

0.5 mm layer thickness (dashed lines)
Halted
Penetrated
1 mm layer thickness
Penetrated
×10^5
0
-2
-4
-6
-8
-10
Projectile velocity [mm/s]
t20-1mm
t20-0.5mm
t22.5-1mm
t22.5-0.5mm
t25-1mm
t25-0.5mm
0
0.2
0.4
0.6
0.8
1
1.2
Time [s]
×10^-4
(1 mm layer thickness)
(0.5 mm layer thickness)

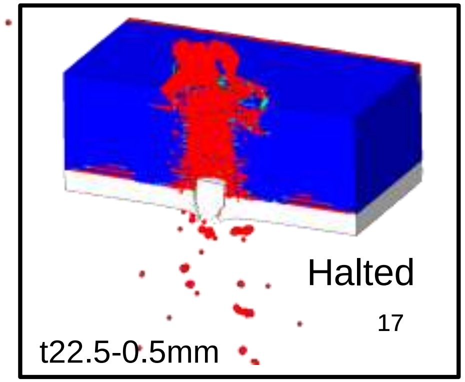

t25-1mm
Penetrated


t25-0.5mm
Halted

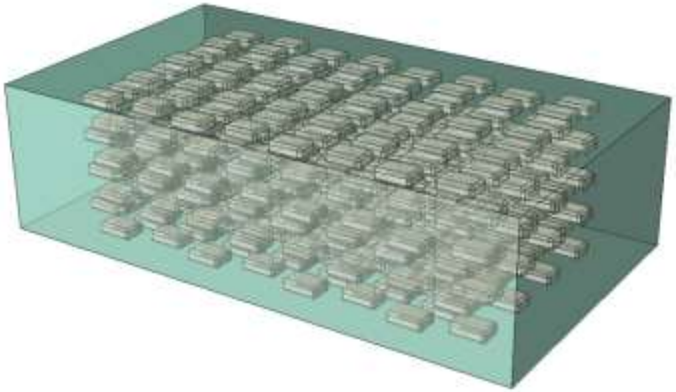

Penetrated
t20-0.5mm

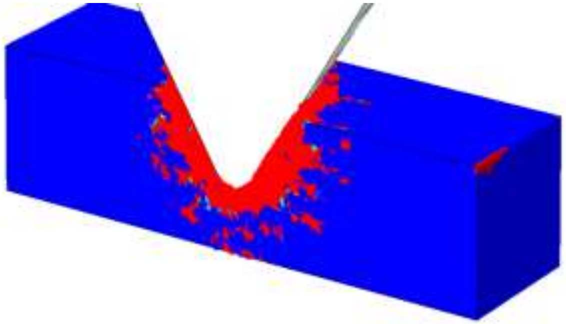

Penetrated
t20-1mm


Penetrated
t22.5-1mm


Halted
t22.5-0.5mm

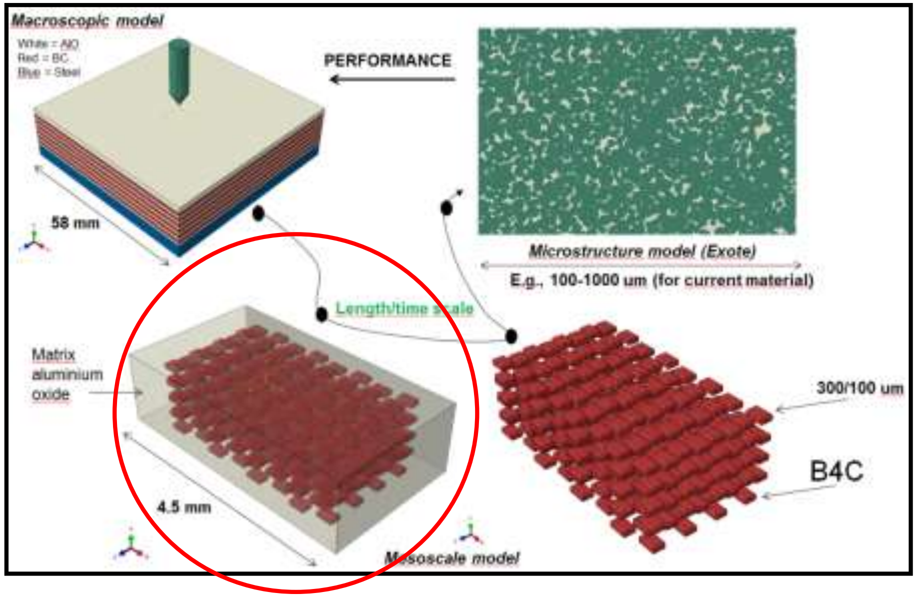
Meso-scale modeling

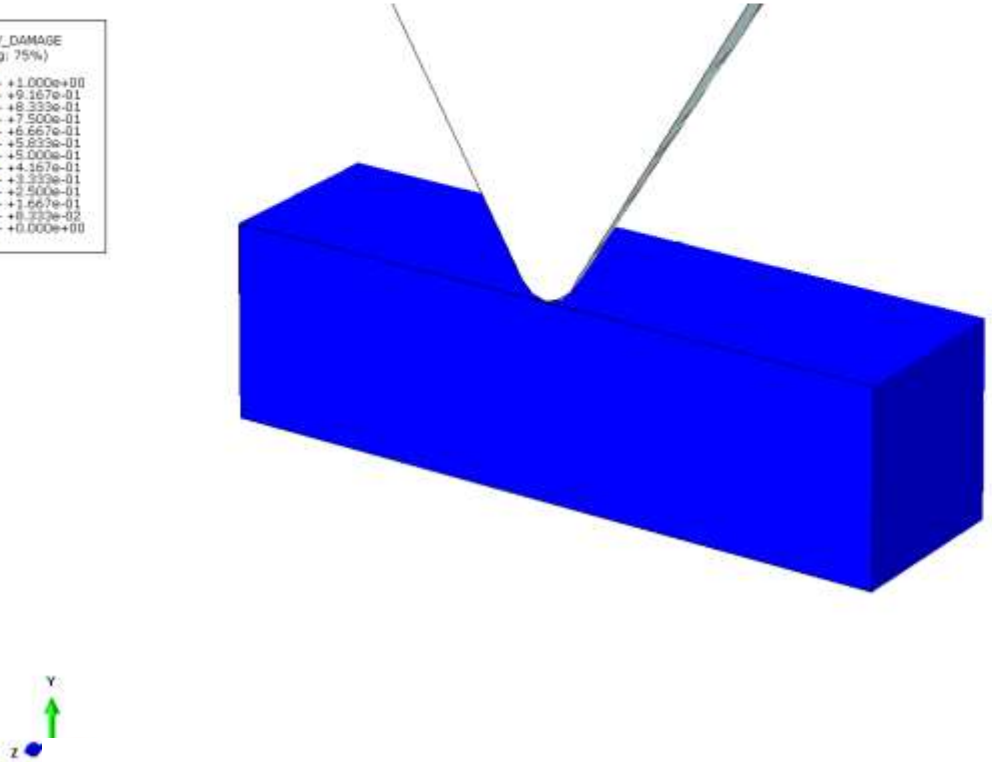




Possibilities

- Optimization of the general structure
- Meso-scale Microstructure
  - Ballistic resistance
  - Energy absorbing structure
  - Lightweight
  - Cost efficiency




V_DAMAGE
g: 75%)
+1.000e+00
+9.167e-01
+8.333e-01
+7.500e-01
+6.667e-01
+5.833e-01
+5.000e-01
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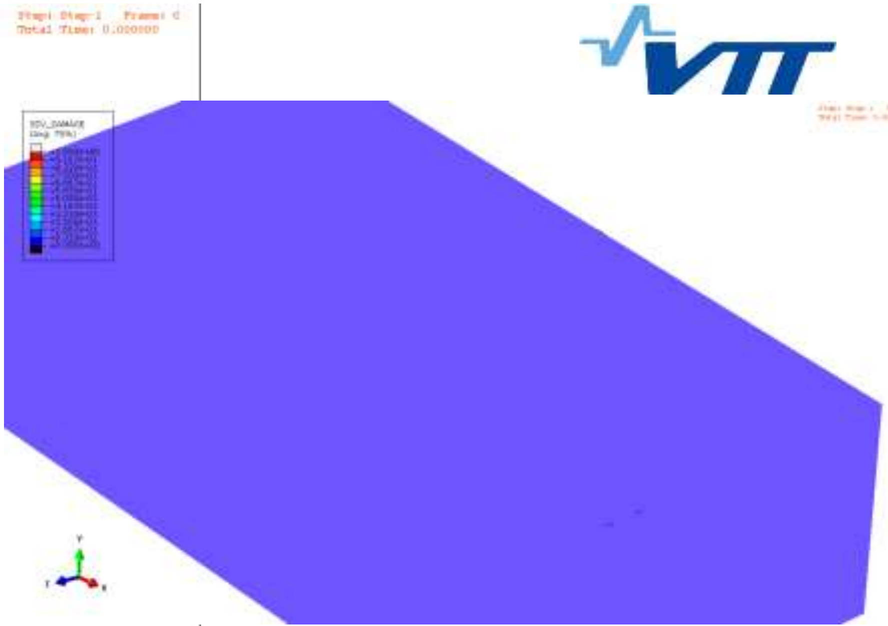
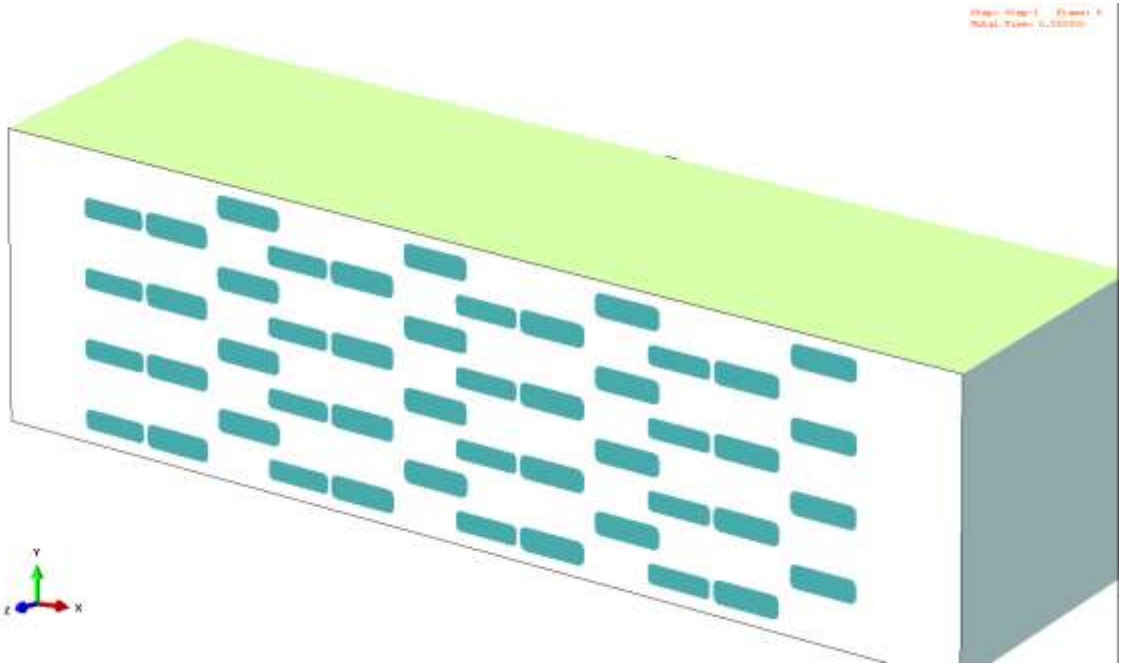
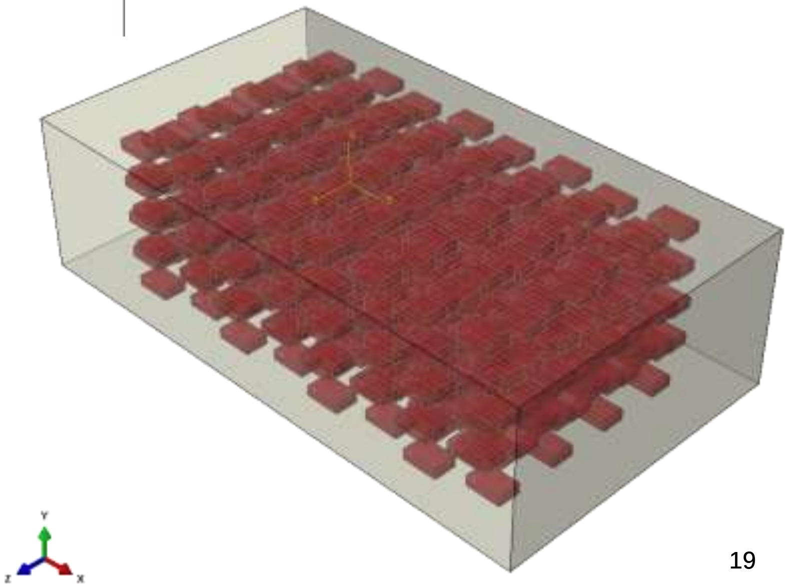
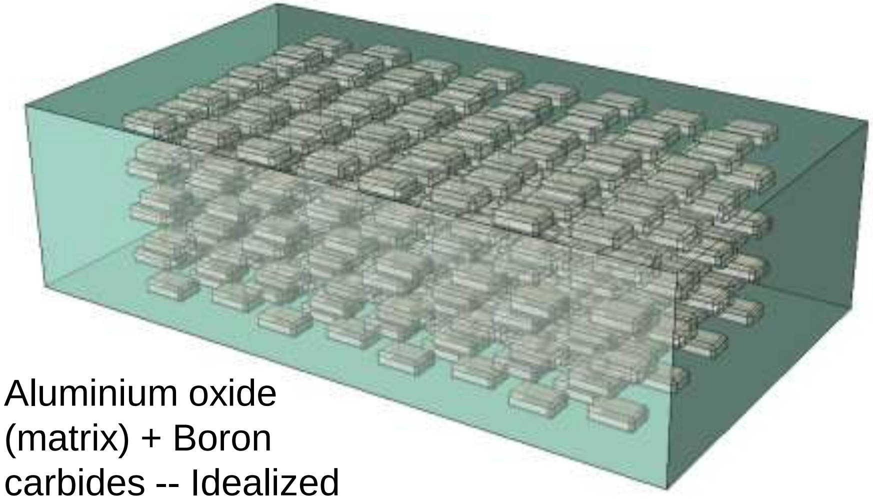
+0.000e+00
Y
Z


Step: Step-1 Frame: 0
Total Time: 0.000000
SDV_DAMAGE
(Avg: 75%)
Y
Z
X


Step: Step-1
Y
Z
X

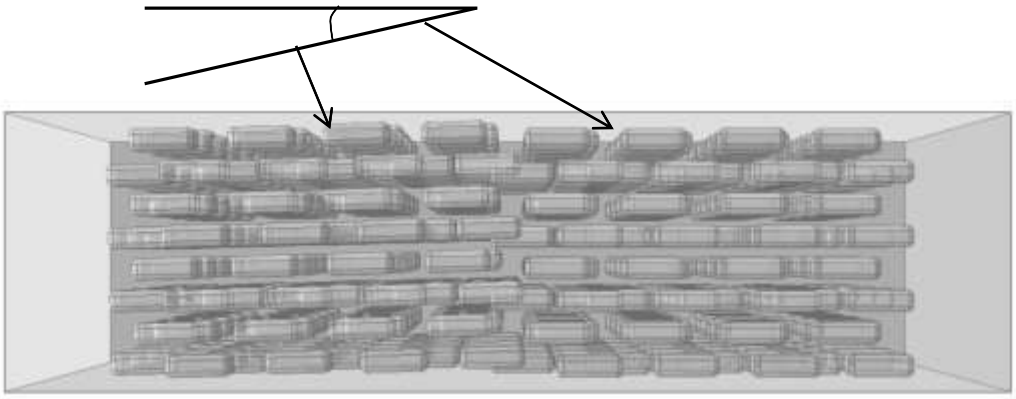

Y
Z
X

Understanding effect of microstructure
-- *Idealized microstructures*



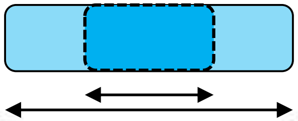
Aluminium oxide (matrix) + Boron carbides -- Idealized

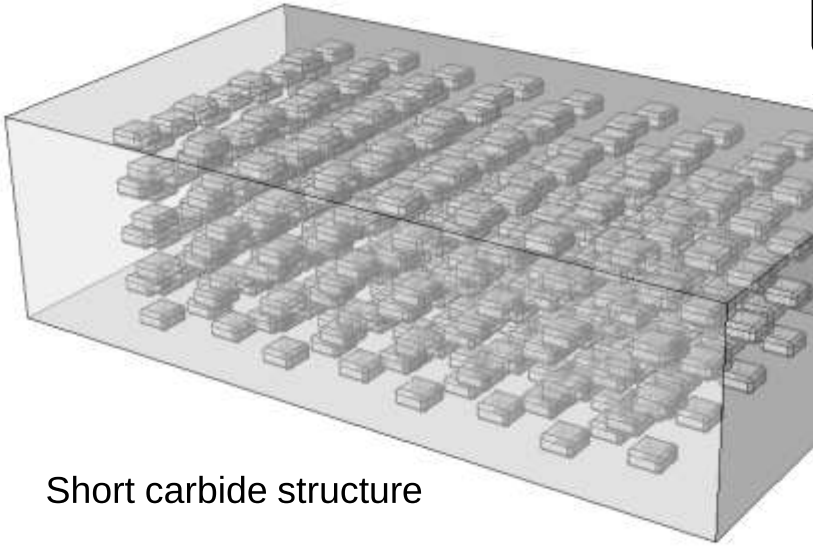
Angularly oriented carbides distribute loading differently



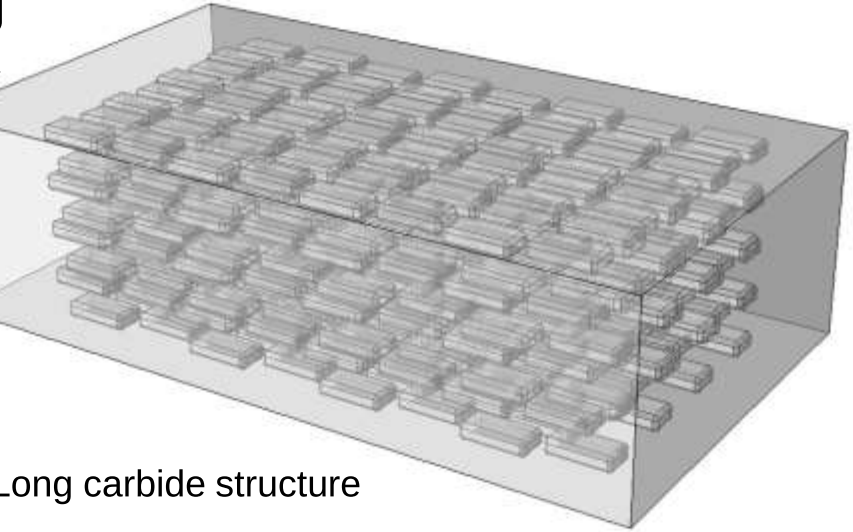
Tilted carbide structure

Carbide aspect ratio and shape factor?

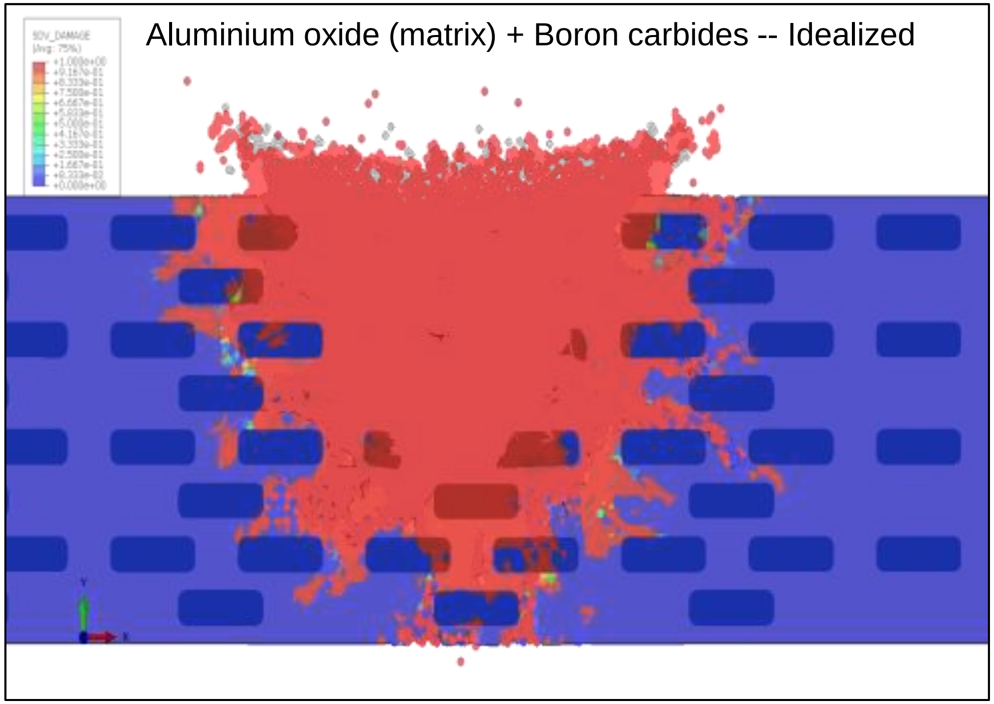




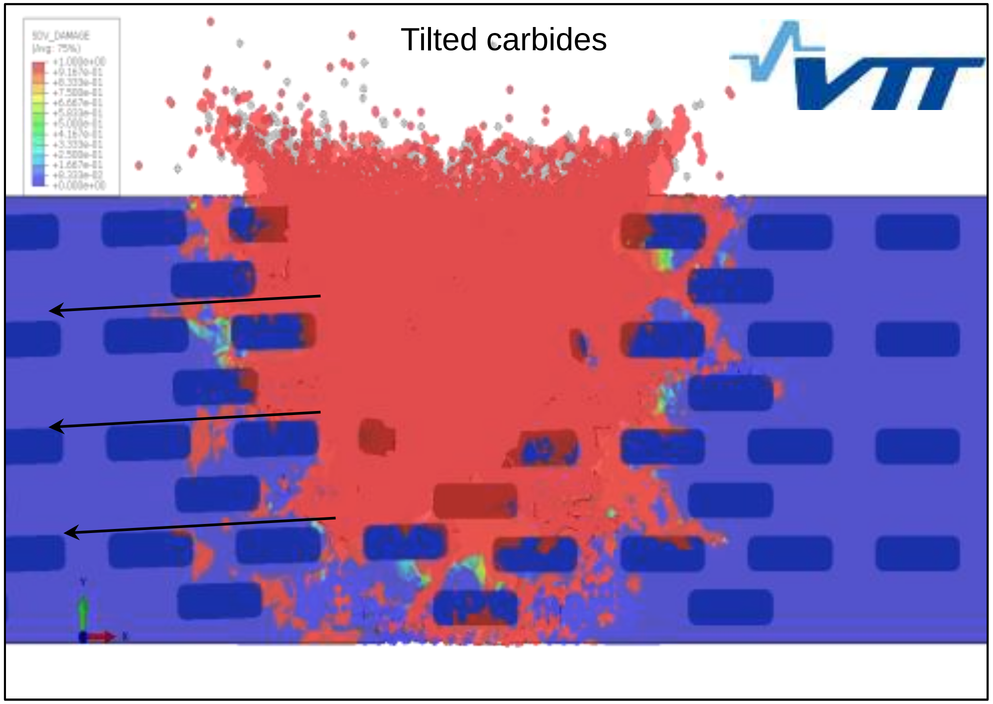
Short carbide structure



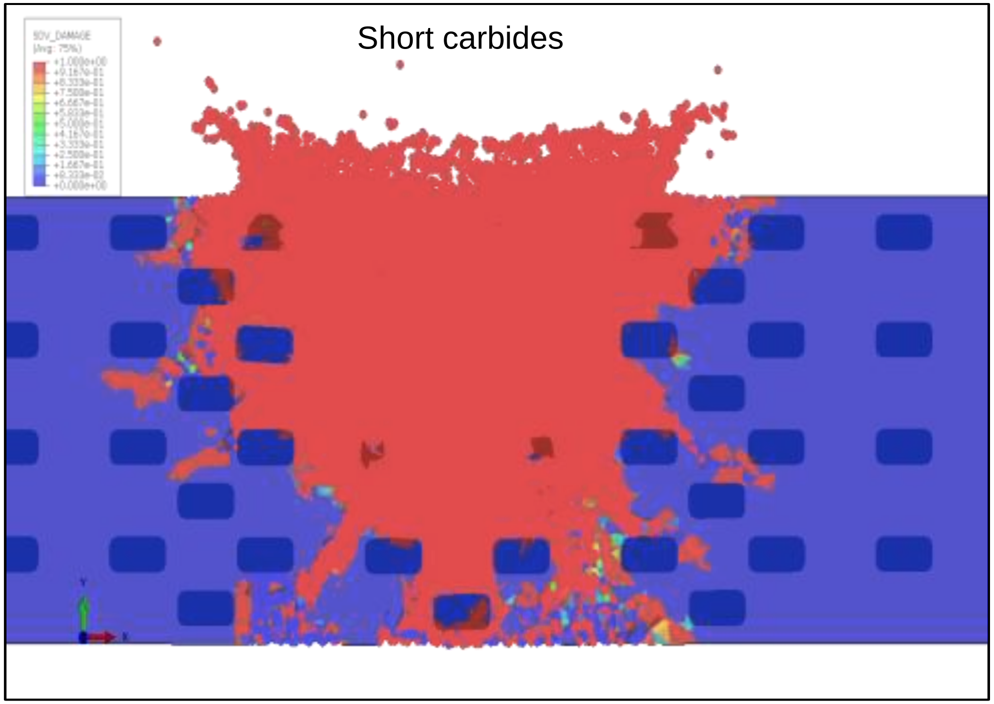
Long carbide structure



Aluminium oxide (matrix) + Boron carbides -- Idealized



Tilted carbides



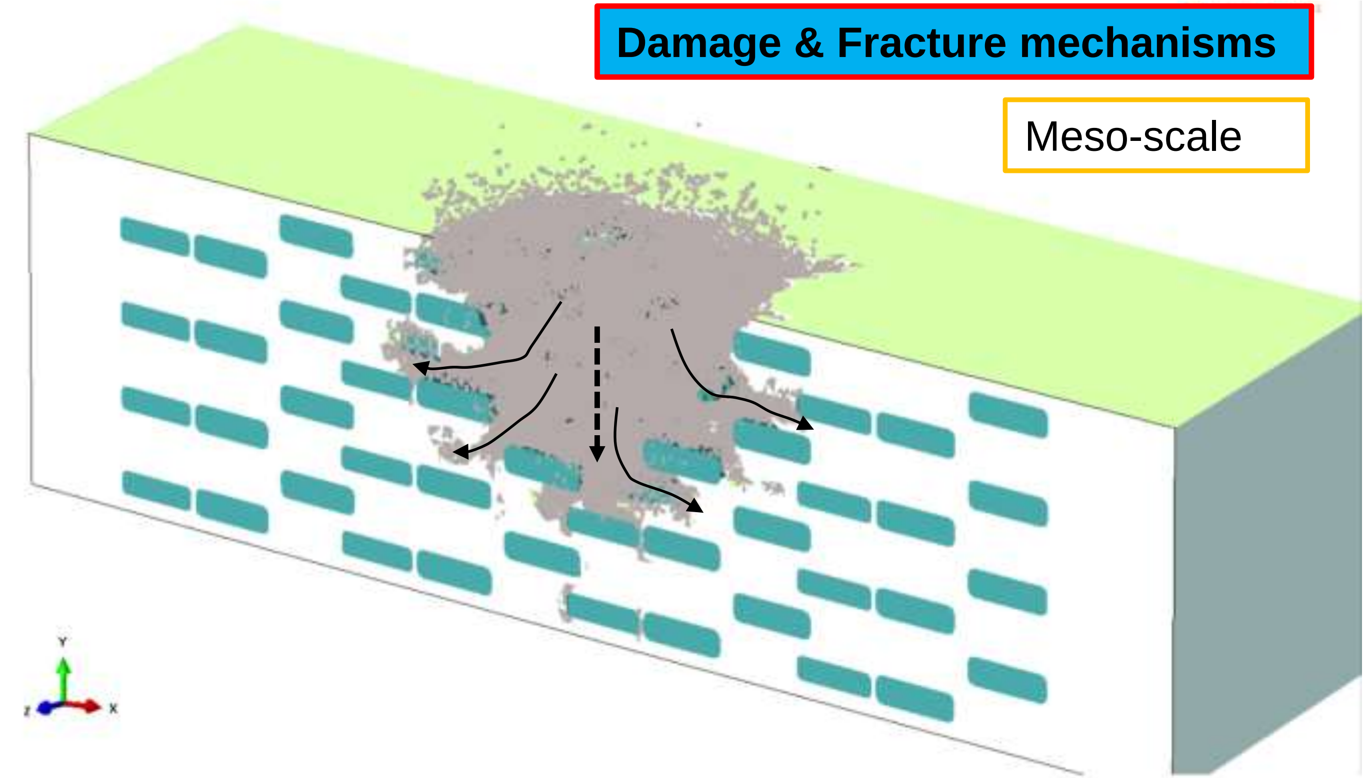
Short carbides

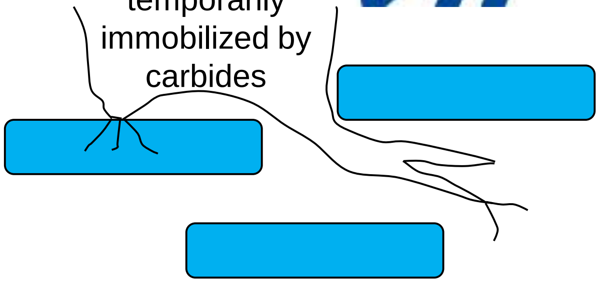
- Damage spreads around the matrix driven by carbide network

- The desired perpendicular crakcing in respect to impact direction (horizontal) increases ballistic resistance of the material as the energy is consumed in in the fracture process

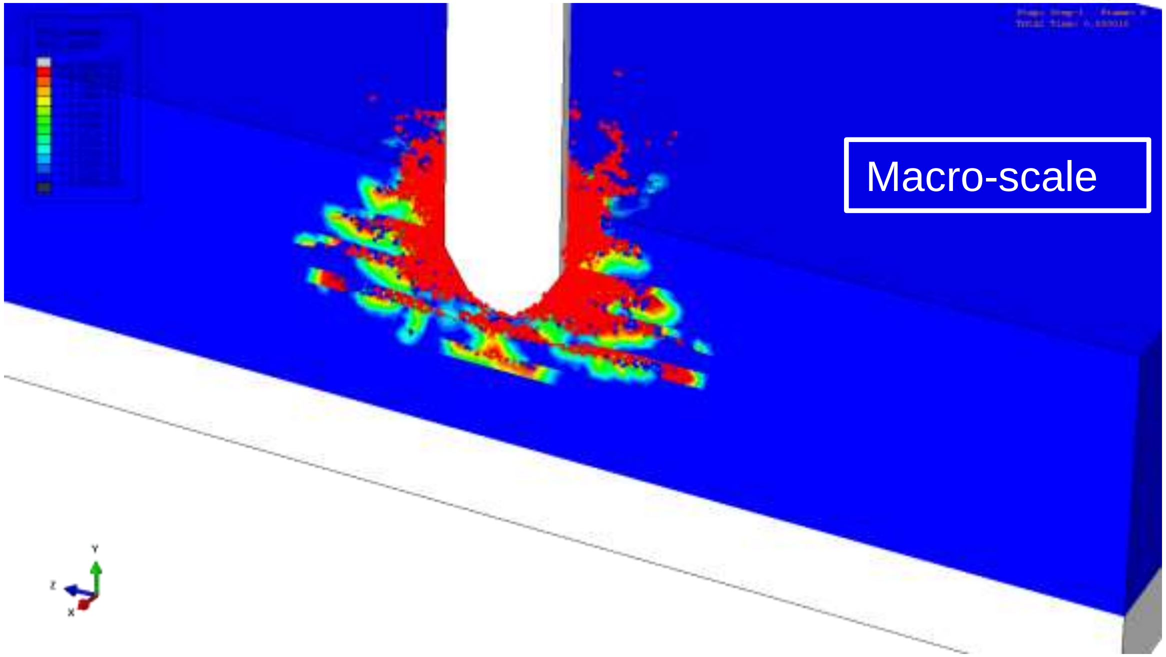
- Tilted carbide structure projects fracture to alternative crack paths, increasing cracking but also consuming more energy;
  - → Optimization requires more studies
- Short carbides increases the volume fraction of matrix → cracking increases, but carbides provide supporting effect

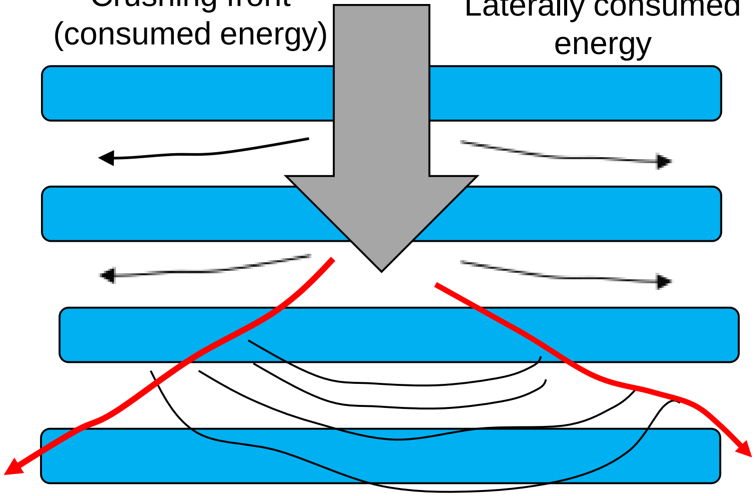
Damage & Fracture mechanisms


Meso-scale


Crack propagation temporarily immobilized by carbides

Energy consumed to various fracture processes


Macro-scale


Crushing front (consumed energy)

Laterally consumed energy

Shock front effect (spalling)

Kaksifaasikeraamit ja reaktiivinen kuumapuristus

$B_2O_3 + Al + C \Rightarrow B_4C + Al_2O_3$

- Dual phase structure simultaneous high hardness and fracture toughens
- Composite structure hinders stress localization in B4C phase
- Cost efficient processing with reactive hot pressing (high temperatures needed in conventional sintering)

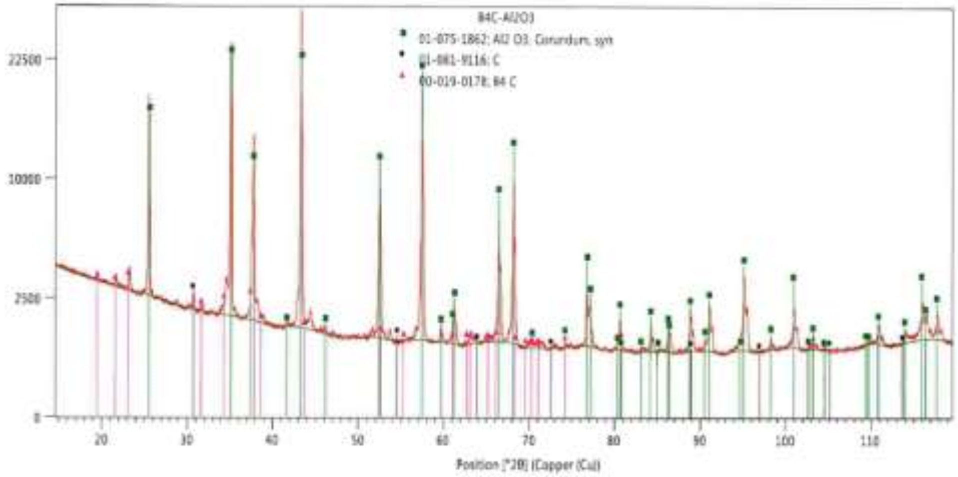
B4C
Density = 2.52 g/cm^3
Melting = 2763 °C
Hardness =3050 HV

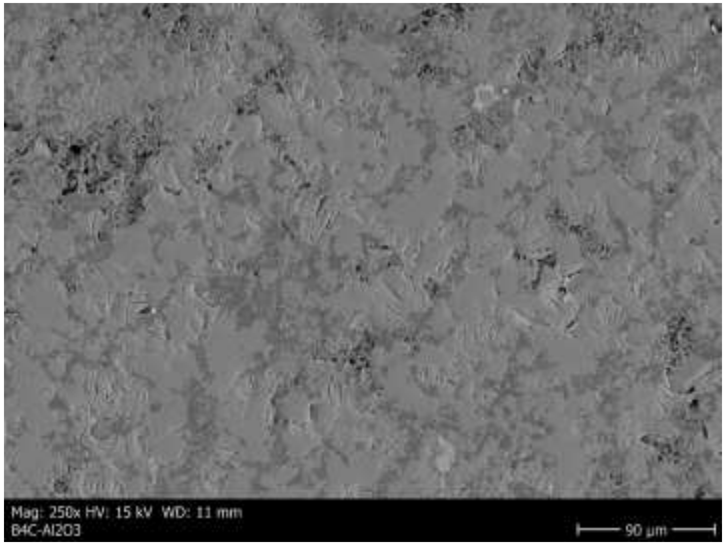
Al2O3
Density = 3.987g/cm^3
Melting = 2072°C
Hardness =1730HV

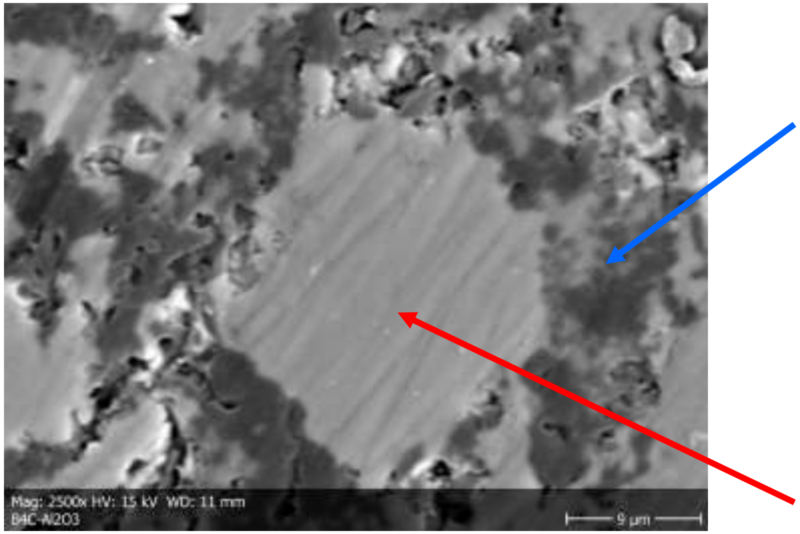
- ➔ *Narrow processing window due to high melting points ➔ cracking & porosity*
- ➔ *Lamellar structure perpendicular pressing direction observed in the first experiments*
- ➔ *Decrease of porosity lead diminishing lamellar phase structure*
- ➔ *High hardness 2000-2500HV1*

Kaksifaasikeraamit ja reaktiivinen kuumapuristus

$B_2O_3 + Al + C \Rightarrow B_4C + Al_2O_3$







Quantitative Results

Elt	XRay	Int	Error	K	Kratio	W%	A%	ZAF
B	Ka	169.4	18.0571	0.7271	0.3728	65.85	82.14	0.5661
C	Ka	47.2	18.0571	0.0179	0.0092	11.93	13.40	0.0770
O	Ka	42.4	18.0571	0.0062	0.0032	1.41	1.19	0.2251
Al	Ka	778.7	41.0013	0.0712	0.0365	4.28	2.14	0.8520
Au	La	18.4	0.9218	0.1775	0.0910	16.52	1.13	0.5510
				1.0000	0.5127	100.00	100.00	

Quantitative Results

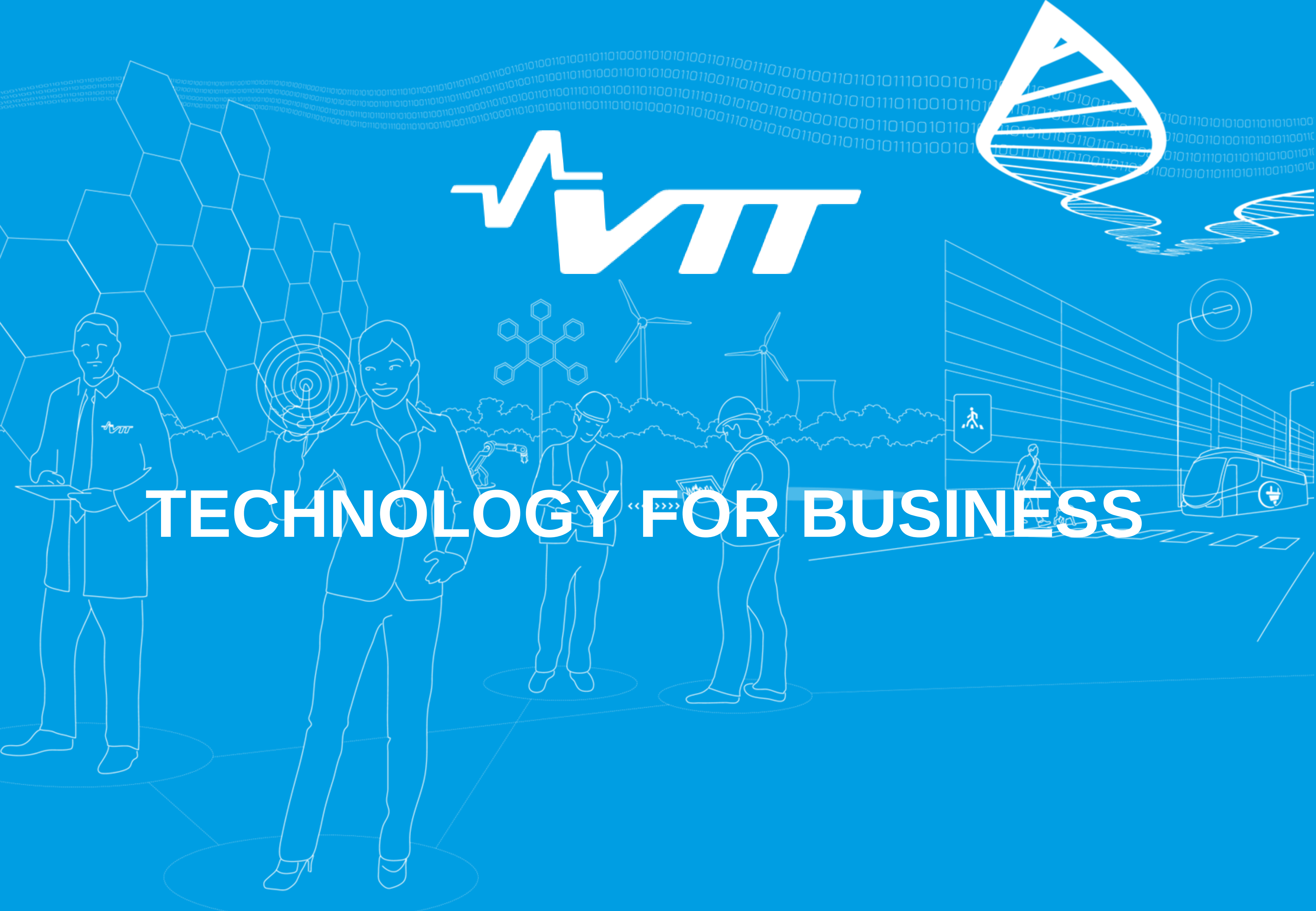
Elt	XRay	Int	Error	K	Kratio	W%	A%	ZAF
O	Ka	441.5	14.2329	0.4408	0.2774	53.78	66.24	0.5159
Al	Ka	895.51	895.3965	0.5592	0.3520	46.22	33.76	0.7614
				1.0000	0.6294	100.00	100.00	

Yhteenveto

- Idea kaksifaasikeraamin toiminnasta osoitettu mallinuksella toimivaksi
- Kehitetty mallinnustyökaluja faasi suhteiden sekä dimensioiden vaikutusten analysoimiseksi
    - ➔ Valmiudet oikean kaksifaasisen keraamin mallintamiseen
- Valmistettu reaktiivisella kuumapuristuksella kaksifaasista B4C-Al2O3 keraamia

➔Lamellaarinen rakenne menetetään kun huokoisuus vähenee

➔Lamellaarisuus tuotettava valmistusmenetelmän kautta ➔ 2018 siirrytään kerrostettuihin rakenteisiin



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