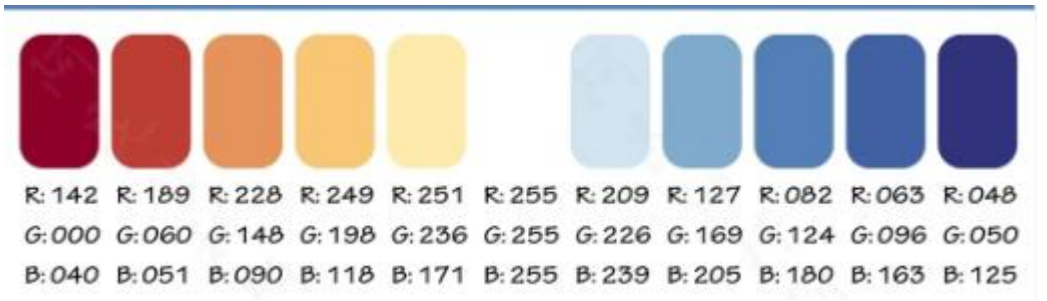
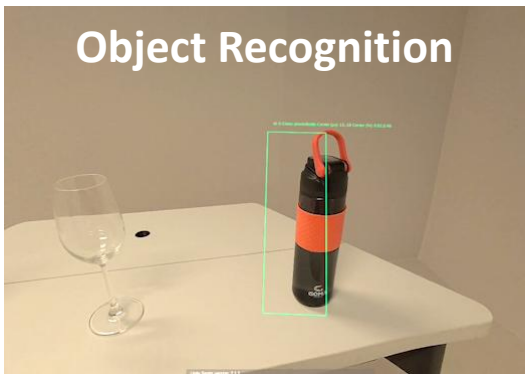
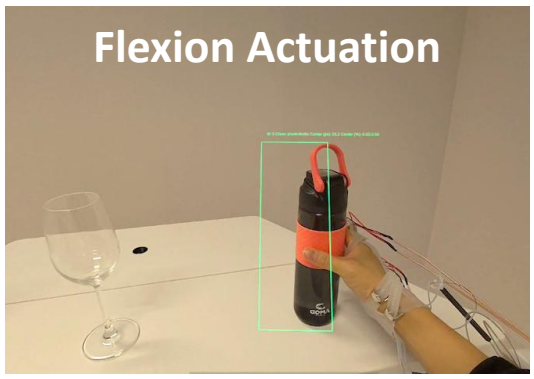
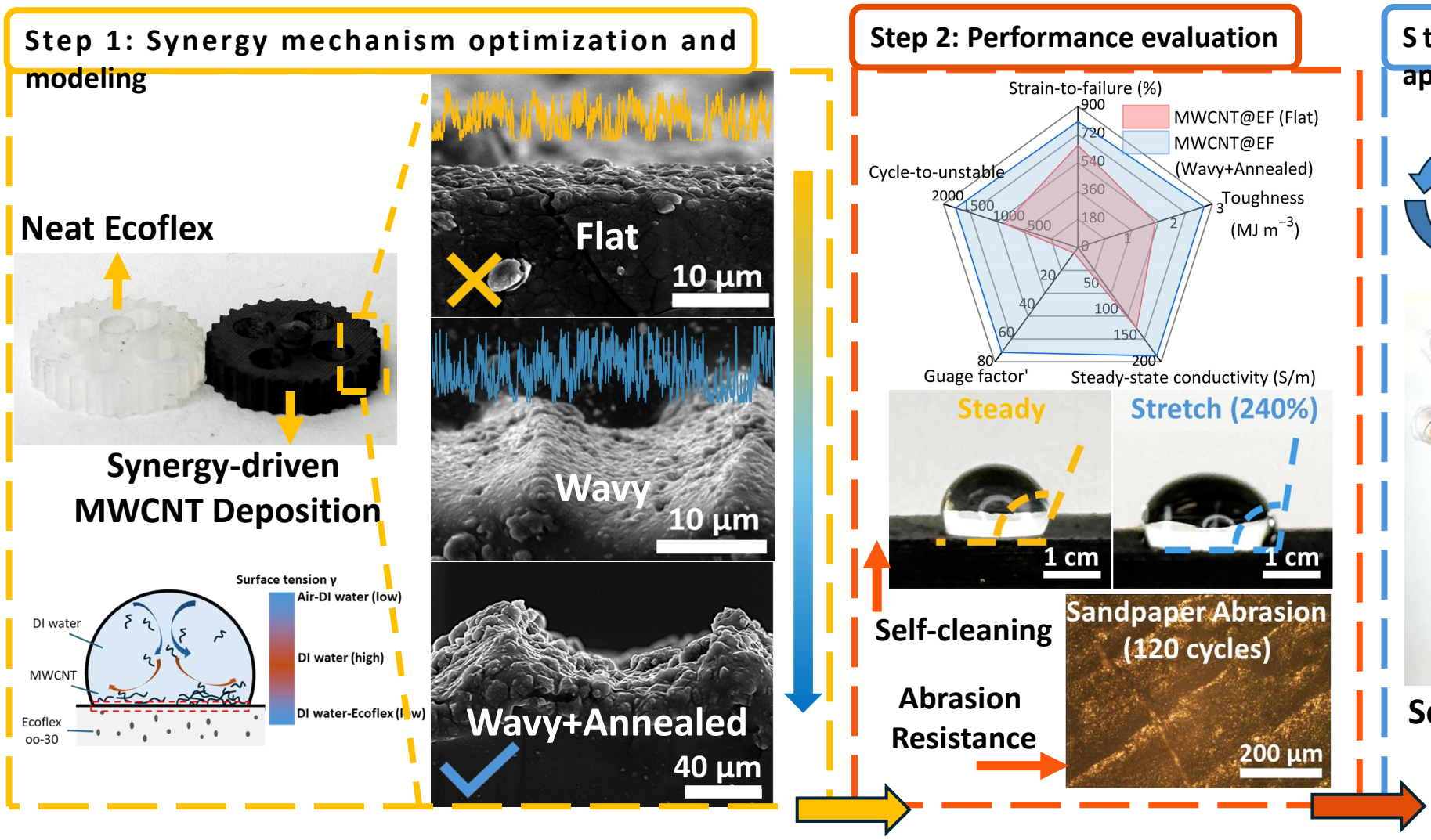
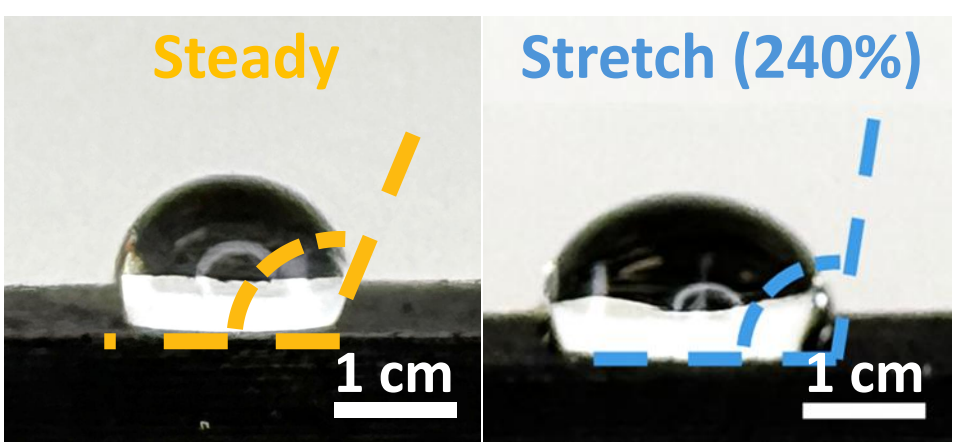

R: 142 R: 189 R: 228 R: 249 R: 251 R: 255 R: 209 R: 127 R: 082 R: 063 R: 048
G: 000 G: 060 G: 148 G: 198 G: 236 G: 255 G: 226 G: 169 G: 124 G: 096 G: 050
B: 040 B: 051 B: 090 B: 118 B: 171 B: 255 B: 239 B: 205 B: 180 B: 163 B: 125

Material

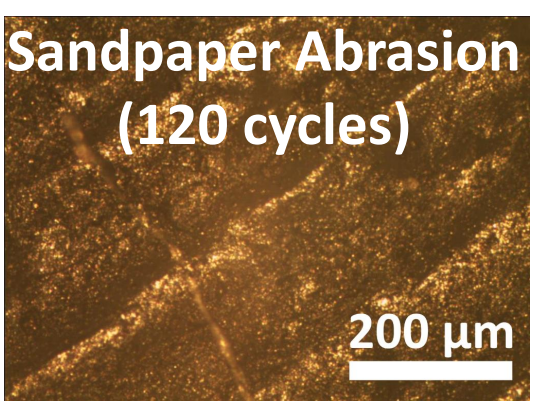


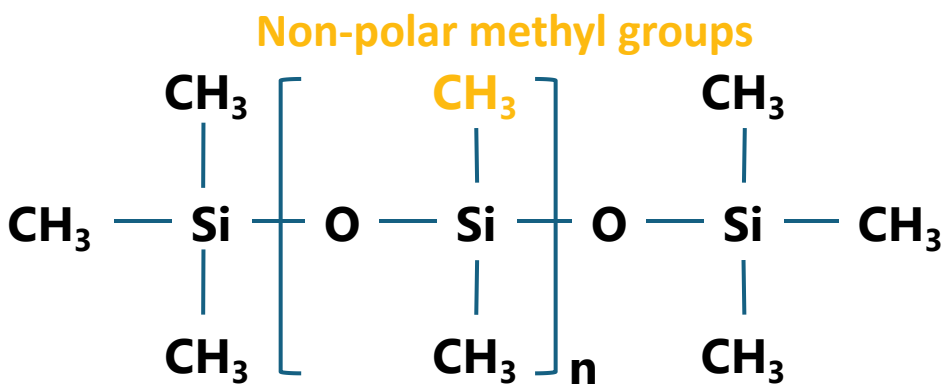


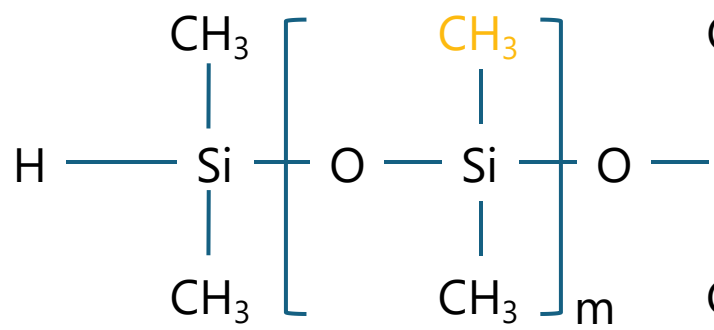


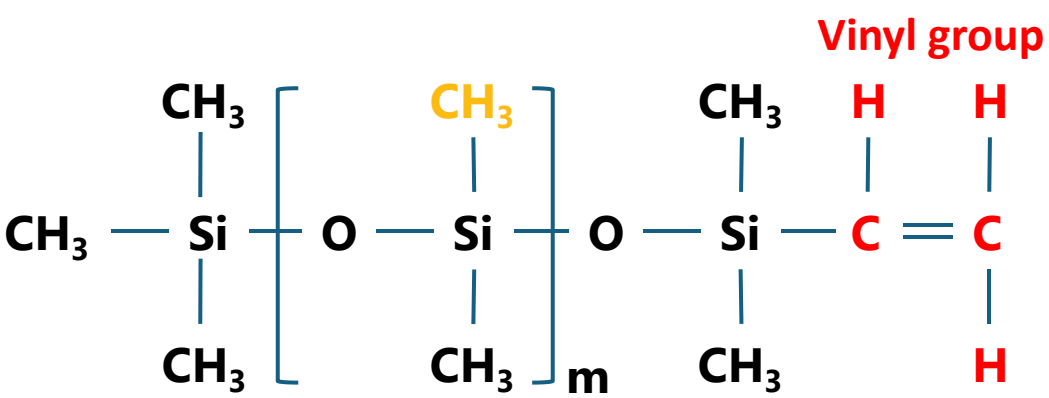


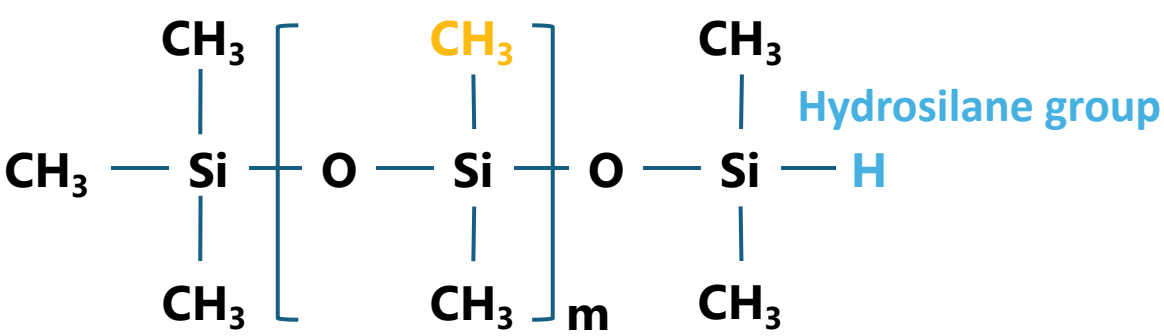
Abrasion Resistance

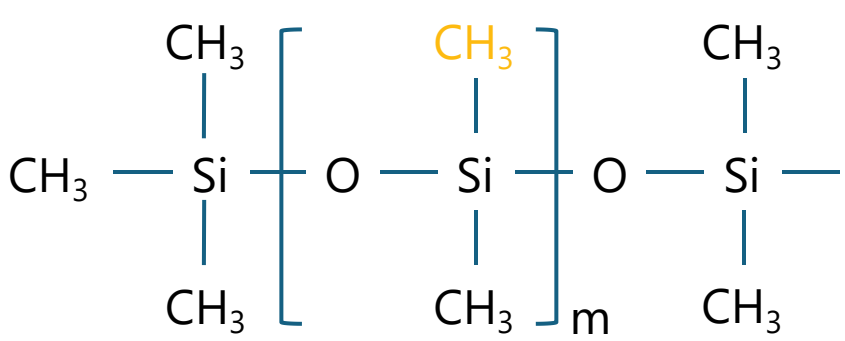


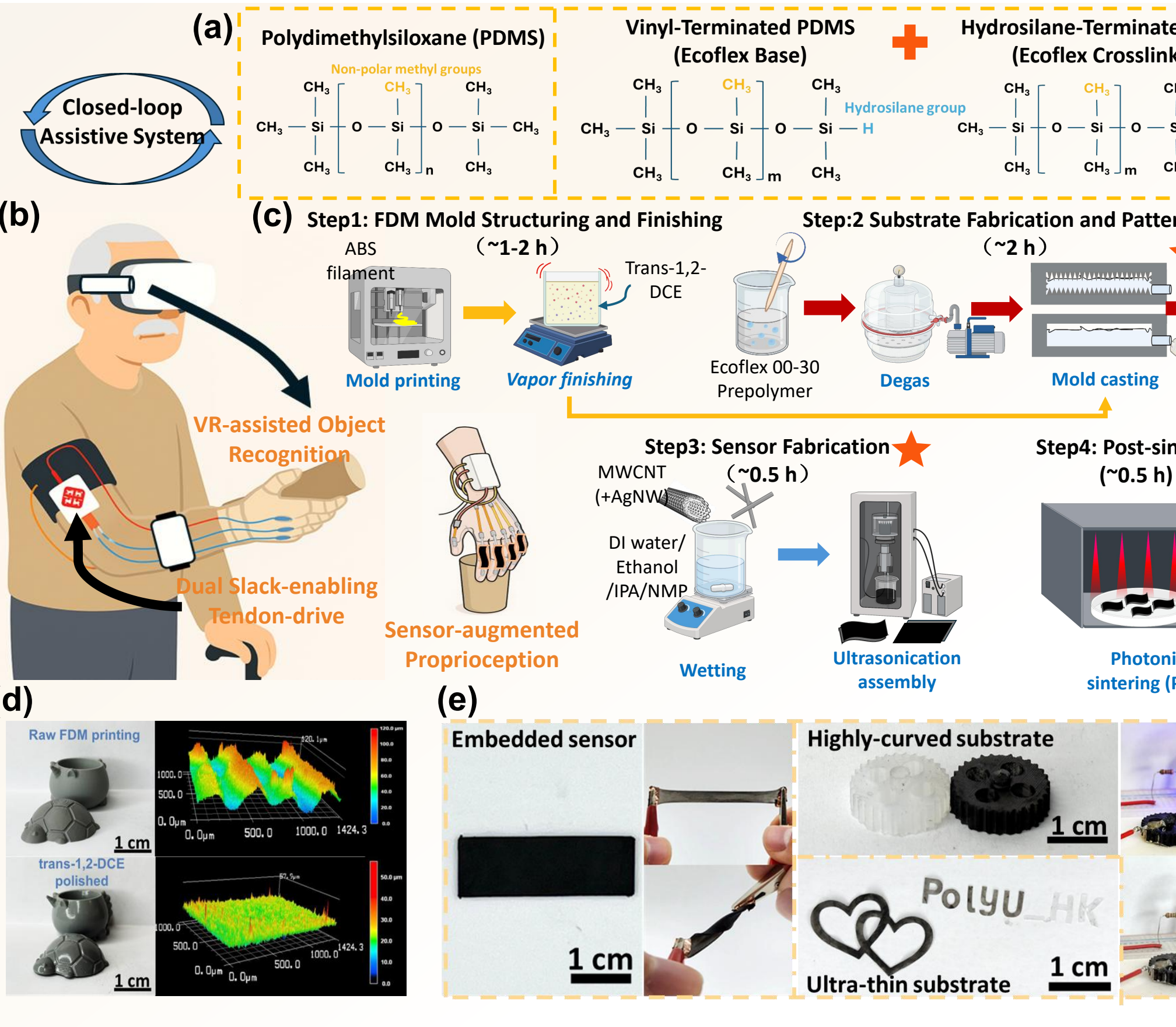

Non-polar methyl groups
CH3
CH3
CH3
CH3
Si
O
Si
O
Si
CH3
CH3
CH3
CH3
n


CH3
CH3
H
Si
O
Si
O
CH3
CH3
m

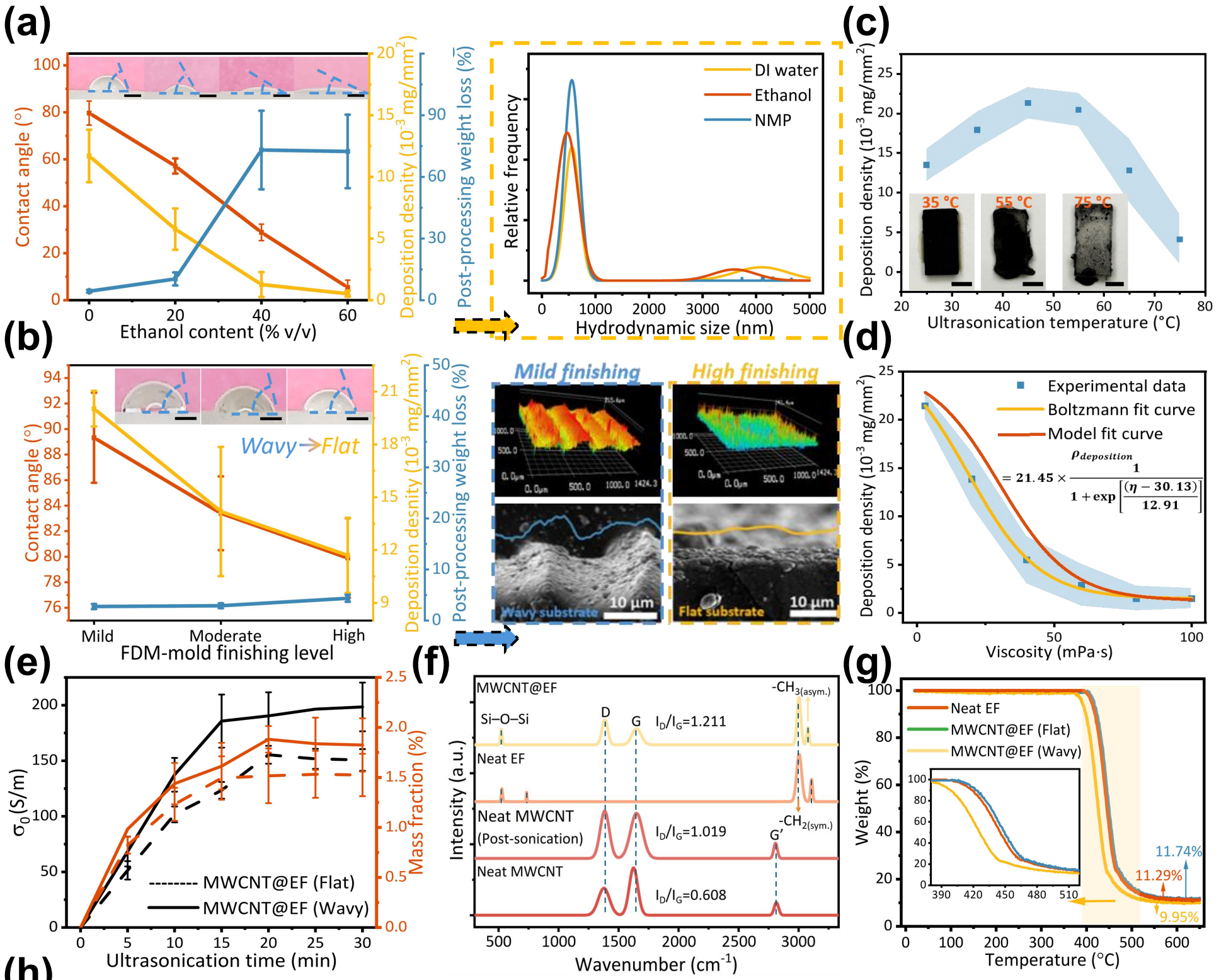

Vinyl group
CH3
CH3
CH3
H
H
CH3
Si
O
Si
O
Si
C
C
CH3
CH3
CH3
H
m

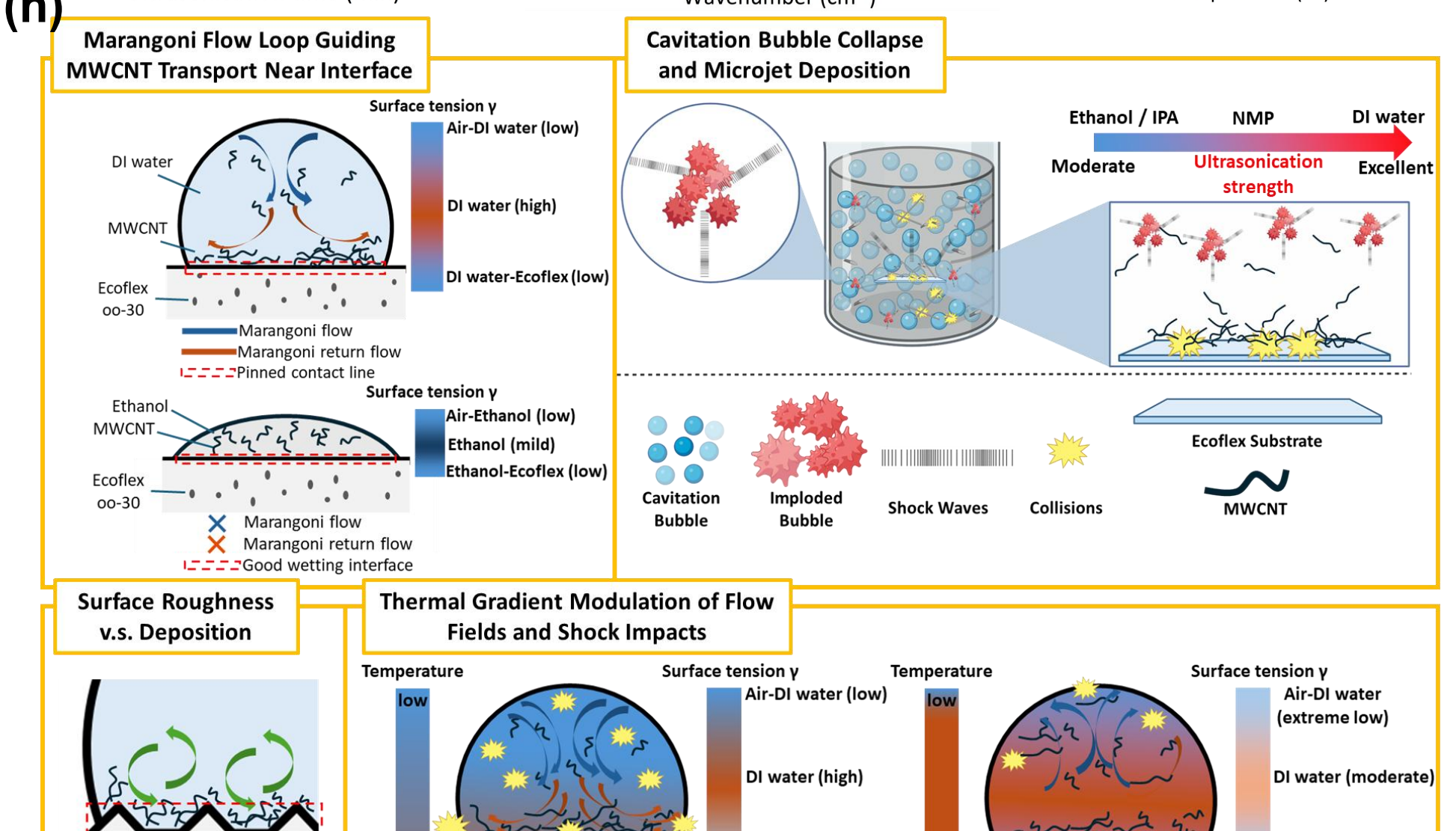

CH3
CH3
CH3
Hydrosilane group
CH3
Si
O
Si
O
Si
H
CH3
CH3
CH3
m

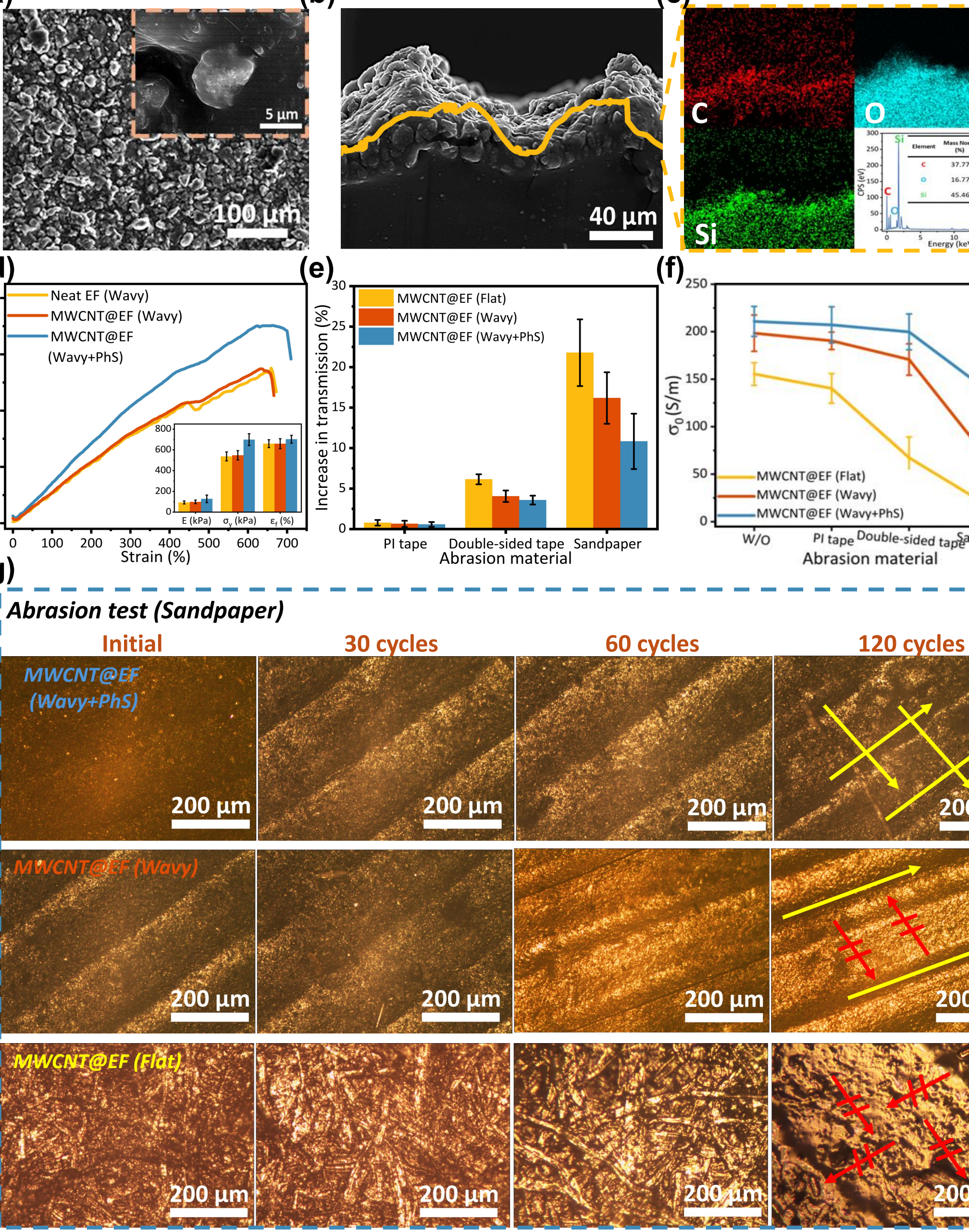

CH3
CH3
CH3
CH3
Si
O
Si
O
Si
CH3
CH3
CH3
m

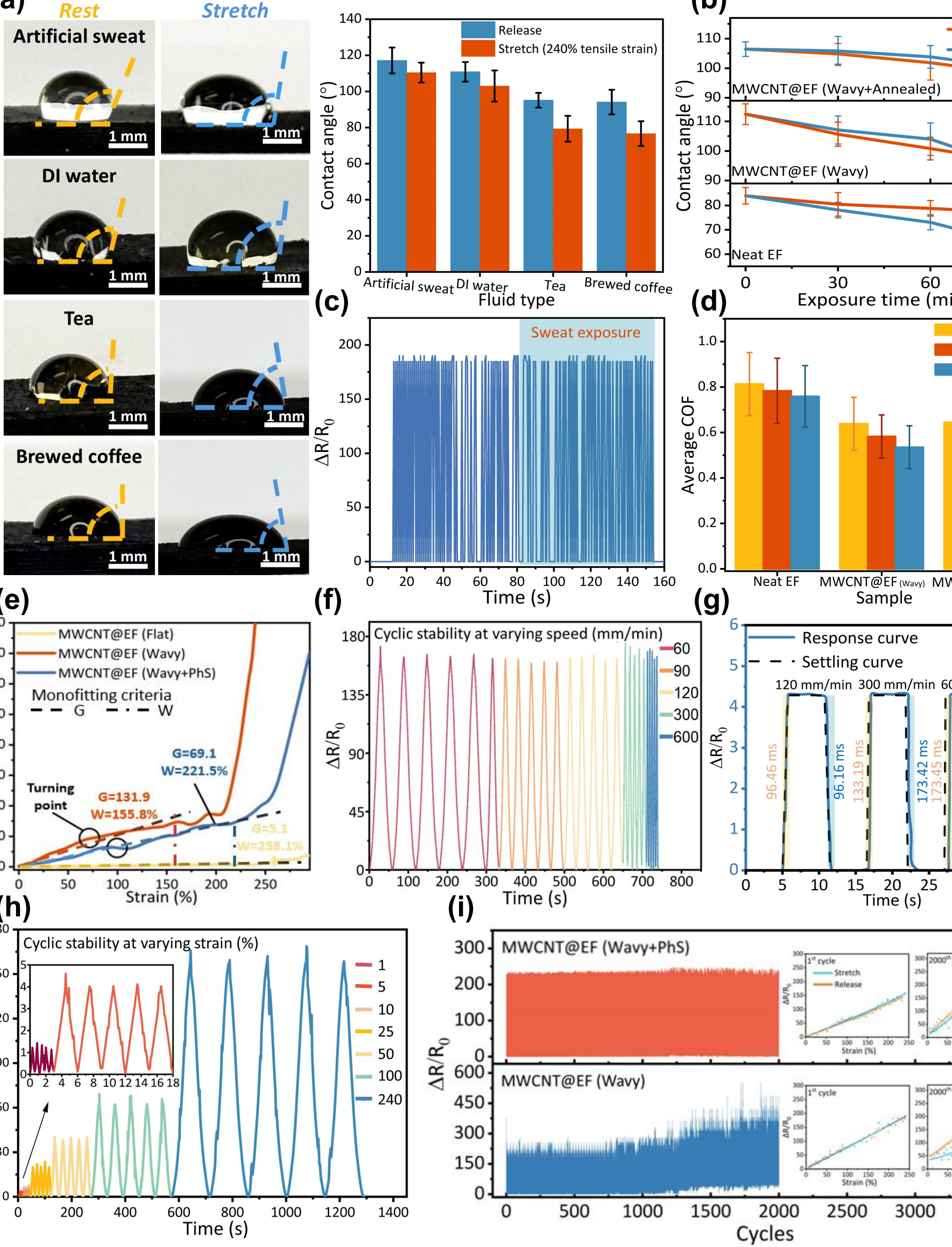

(a)
Closed-loop Assistive System
Polydimethylsiloxane (PDMS)
Non-polar methyl groups
Vinyl-Terminated PDMS (Ecoflex Base)
Hydrosilane-Terminate
(Ecoflex Crosslink
Hydrosilane group
(b)
VR-assisted Object Recognition
Dual Slack-enabling Tendon-drive
(c)
Step1: FDM Mold Structuring and Finishing
(~1-2 h)
ABS filament
Trans-1,2-DCE
Mold printing
Vapor finishing
Step:2 Substrate Fabrication and Patter
(~2 h)
Ecoflex 00-30 Prepolymer
Degas
Mold casting
Step3: Sensor Fabrication
(~0.5 h)
MWCNT (+AgNW)
DI water/ Ethanol /IPA/NMP
Wetting
Ultrasonication assembly
Step4: Post-sin
(~0.5 h)
Photoni
sintering (P
Sensor-augmented Proprioception
(d)
Raw FDM printing
1 cm
trans-1,2-DCE polished
1 cm
(e)
Embedded sensor
1 cm
Highly-curved substrate
1 cm
PolyU_HK
Ultra-thin substrate
1 cm

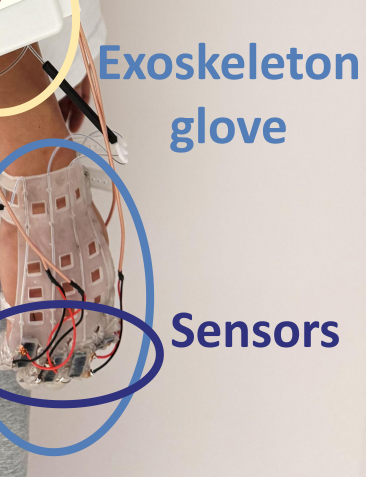
Cyc

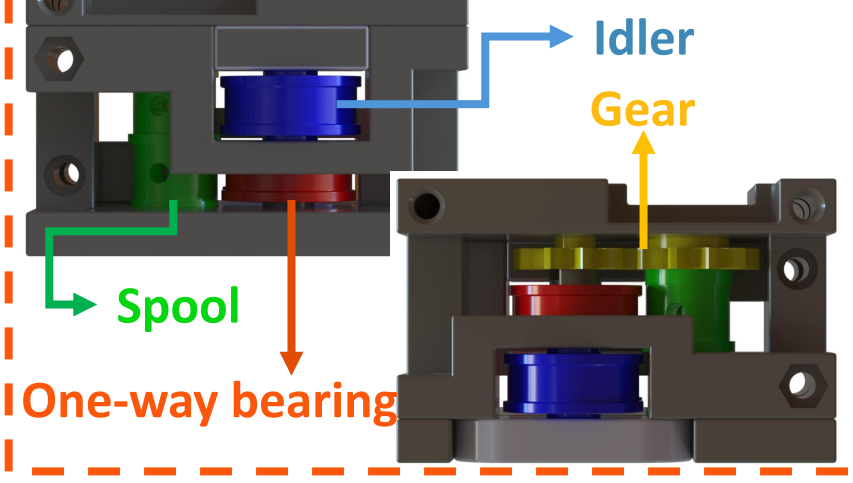

(a)
Contact angle (°)
Deposition desnity (10^{-3} mg/mm^2)
Post-processing weight loss (%)
Ethanol content (% v/v)
DI water
Ethanol
NMP
Relative frequency
Hydrodynamic size (nm)
(c)
Deposition density (10^{-3} mg/mm^2)
35 °C
55 °C
75 °C
Ultrasonication temperature (°C)
(b)
Wavy→Flat
Mild finishing
High finishing
Wavy substrate
Flat substrate
10 μm
Mild
Moderate
High
FDM-mold finishing level
(d)
Experimental data
Boltzmann fit curve
Model fit curve
$\rho_{deposition} = 21.45 \times \frac{1}{1+\exp\left[\frac{(\eta-30.13)}{12.91}\right]}$
Viscosity (mPa·s)
(e)
σ_0(S/m)
Mass fraction (%)
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
Ultrasonication time (min)
(f)
MWCNT@EF
Si–O–Si
D
G
I_D/I_G=1.211
-CH$_{3(asym.)}$
Neat EF
Neat MWCNT (Post-sonication)
I_D/I_G=1.019
G'
-CH$_{2(sym.)}$
Neat MWCNT
I_D/I_G=0.608
Intensity (a.u.)
Wavenumber (cm^{-1})
(g)
Neat EF
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
Weight (%)
11.74%
11.29%
9.95%
Temperature (°C)

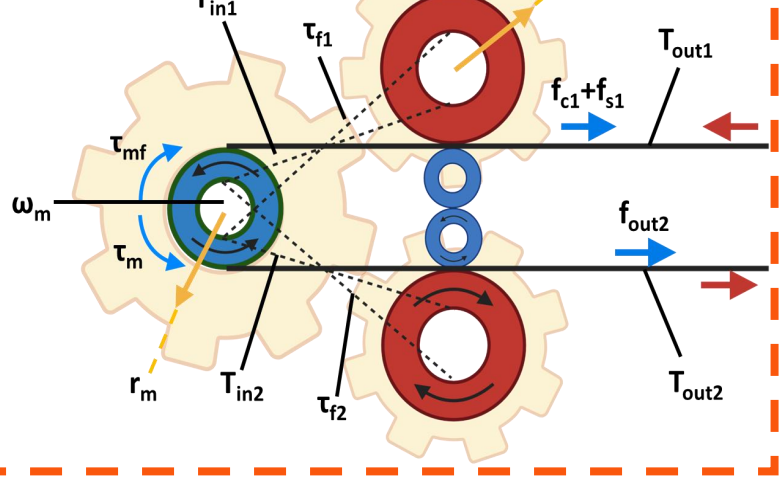

(h)
Marangoni Flow Loop Guiding MWCNT Transport Near Interface
Surface tension γ
Air-DI water (low)
DI water (high)
DI water-Ecoflex (low)
DI water
MWCNT
Ecoflex oo-30
Marangoni flow
Marangoni return flow
Pinned contact line
Ethanol
Air-Ethanol (low)
Ethanol (mild)
Ethanol-Ecoflex (low)
Good wetting interface
Cavitation Bubble Collapse and Microjet Deposition
Ethanol / IPA
NMP
DI water
Moderate
Ultrasonication strength
Excellent
Cavitation Bubble
Imploded Bubble
Shock Waves
Collisions
Ecoflex Substrate
MWCNT
Surface Roughness v.s. Deposition
Thermal Gradient Modulation of Flow Fields and Shock Impacts
Temperature
low
Air-DI water (extreme low)
DI water (moderate)

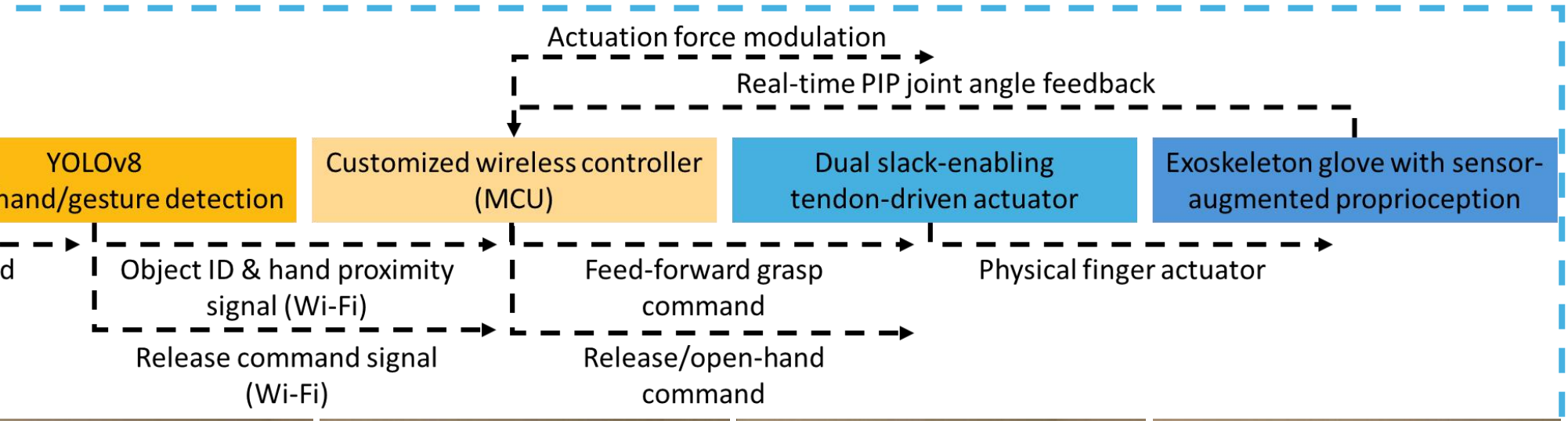

5 µm
100 µm
40 µm
C
O
Si
Element
Mass Nor (%)
c 37.77
o 16.77
si 45.46
CPS (eV)
Energy (keV)
Neat EF (Wavy)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+PhS)
E (kPa)
σy (kPa)
εf (%)
Strain (%)
(e)
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+PhS)
Increase in transmission (%)
PI tape
Double-sided tape
Sandpaper
Abrasion material
(f)
σ0 (S/m)
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+PhS)
W/O
PI tape
Double-sided tape
Abrasion material
Abrasion test (Sandpaper)
Initial
30 cycles
60 cycles
120 cycles
MWCNT@EF (Wavy+PhS)
MWCNT@EF (Wavy)
MWCNT@EF (Flat)
200 µm

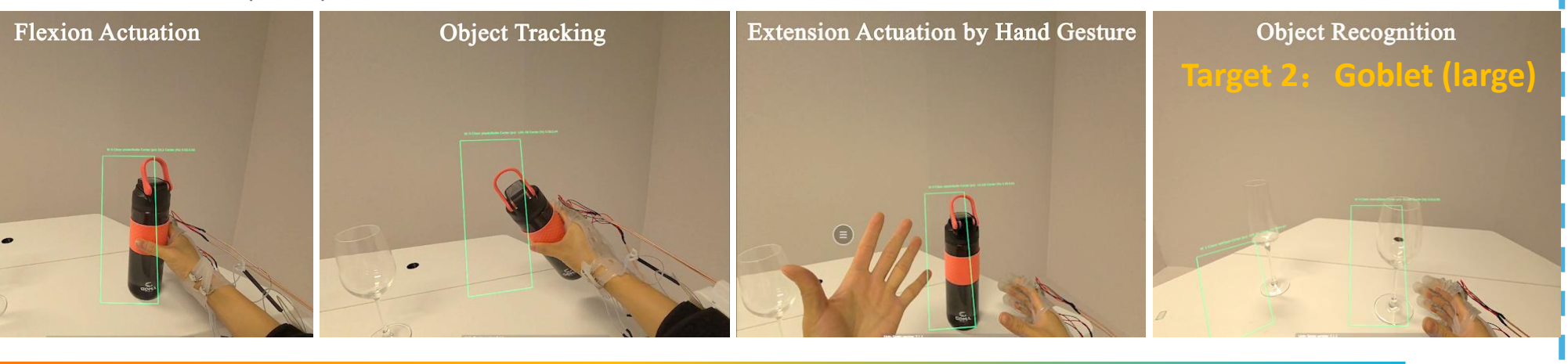

(a)
Rest
Stretch
Artificial sweat
DI water
Tea
Brewed coffee
1 mm
(b)
Contact angle (°)
MWCNT@EF (Wavy+Annealed)
MWCNT@EF (Wavy)
Neat EF
Exposure time (mi
(c)
Release
Stretch (240% tensile strain)
Contact angle (°)
Artificial sweat
DI water
Tea
Brewed coffee
Fluid type
(d)
Average COF
Neat EF
MWCNT@EF (Wavy)
Sample
(e)
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+PhS)
Monofitting criteria
G
W
G=69.1
W=221.5%
Turning point
G=131.9
W=155.8%
G=5.1
W=258.1%
Strain (%)
(f)
Sweat exposure
ΔR/R0
Time (s)
(g)
Cyclic stability at varying speed (mm/min)
60
90
120
300
600
ΔR/R0
Time (s)
(h)
Response curve
Settling curve
120 mm/min
300 mm/min
96.46 ms
96.16 ms
133.19 ms
173.42 ms
173.45 ms
ΔR/R0
Time (s)
(i)
Cyclic stability at varying strain (%)
1
5
10
25
50
100
240
Time (s)
MWCNT@EF (Wavy+PhS)
MWCNT@EF (Wavy)
1st cycle
Stretch
Release
Strain (%)
ΔR/R0
Cycles



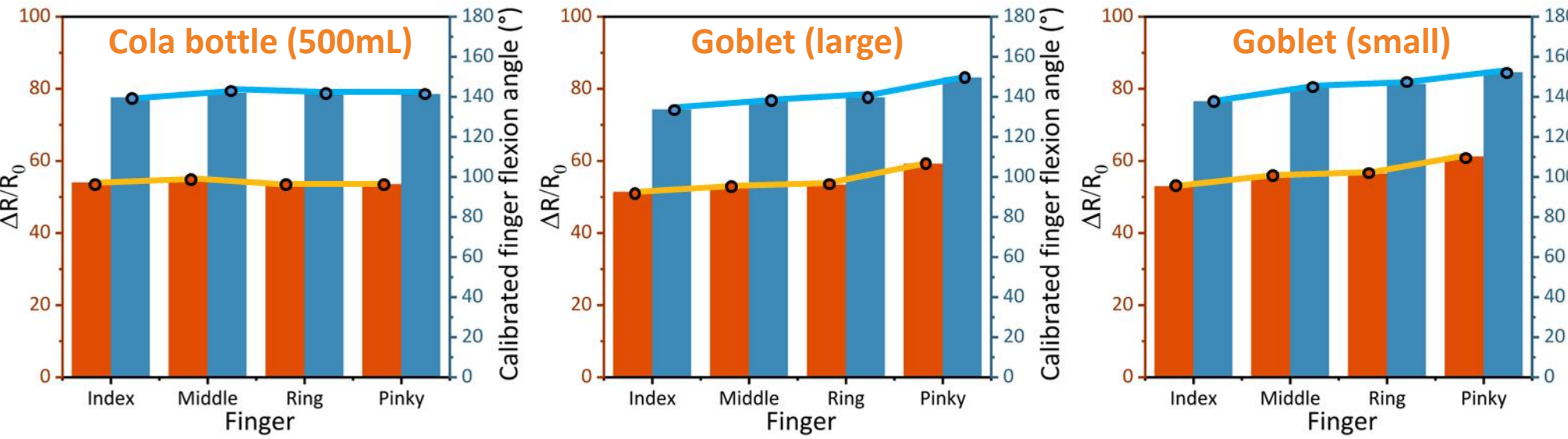


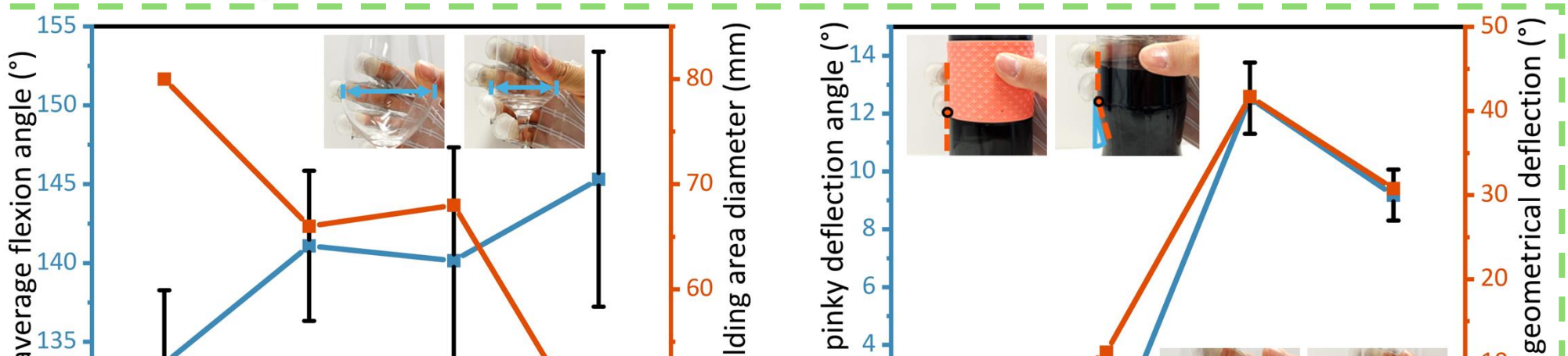


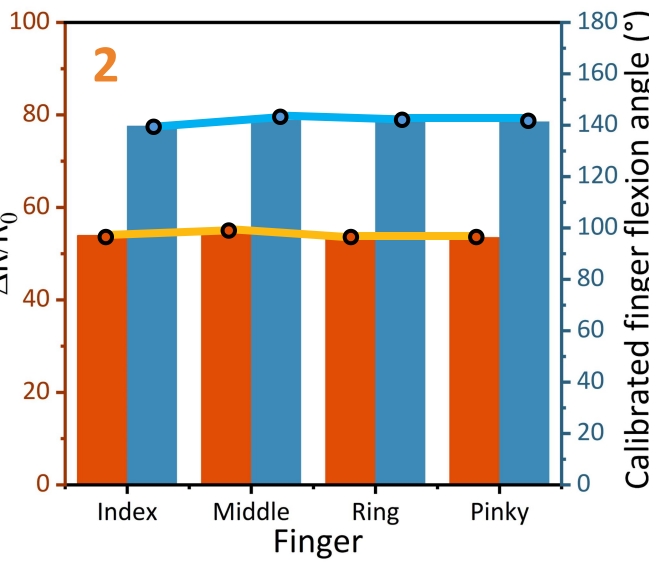


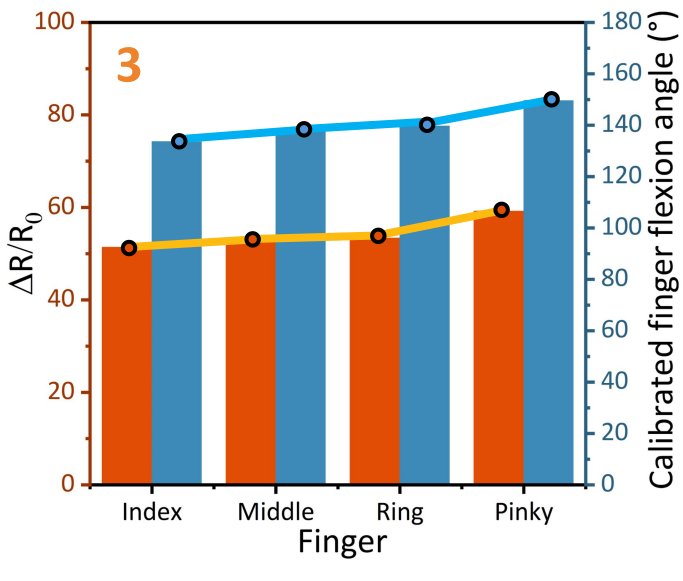


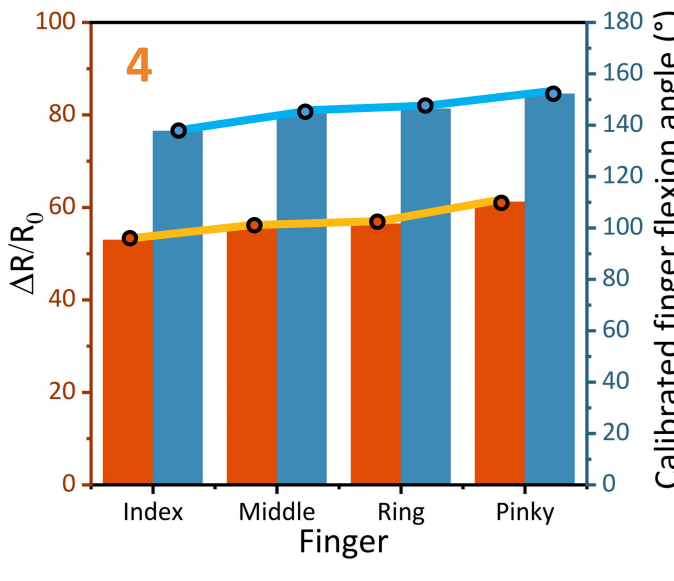
Closed-Loop Assistive Exoskeleton Workflow

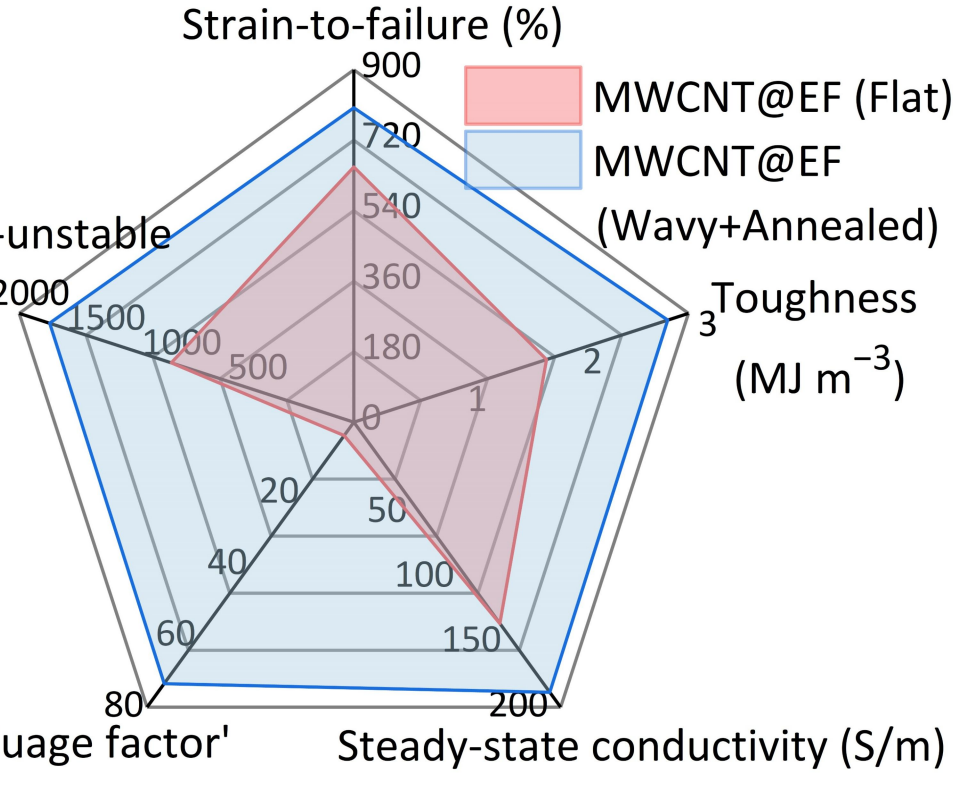


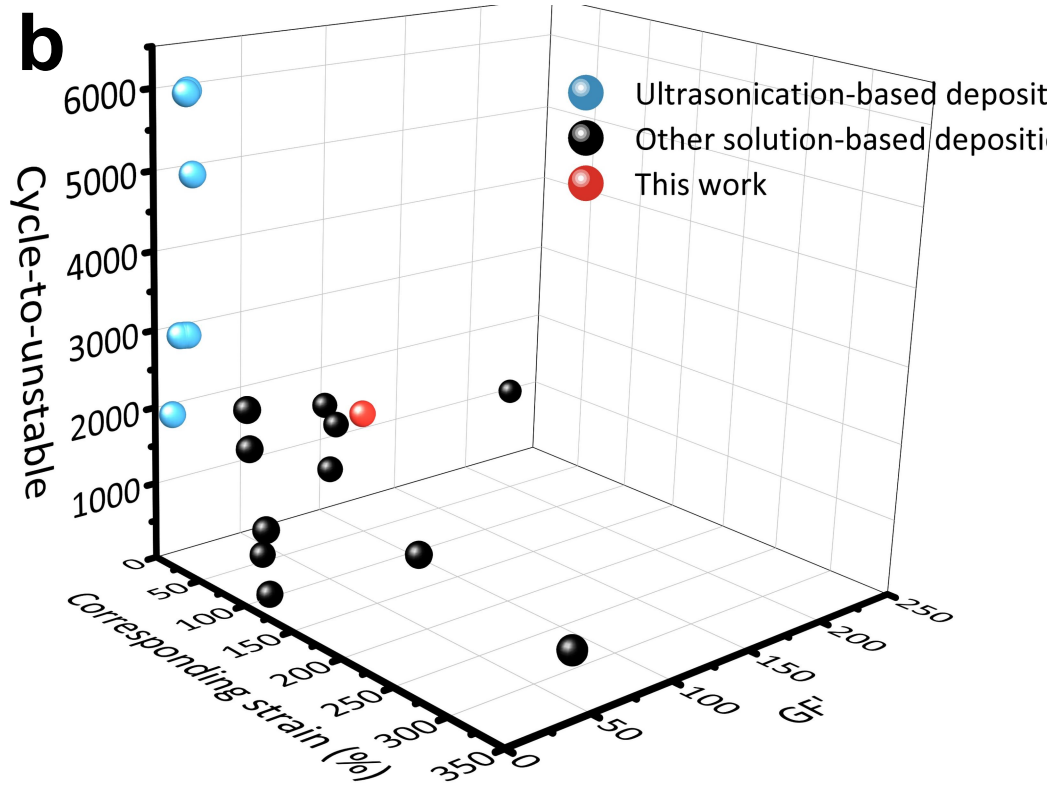


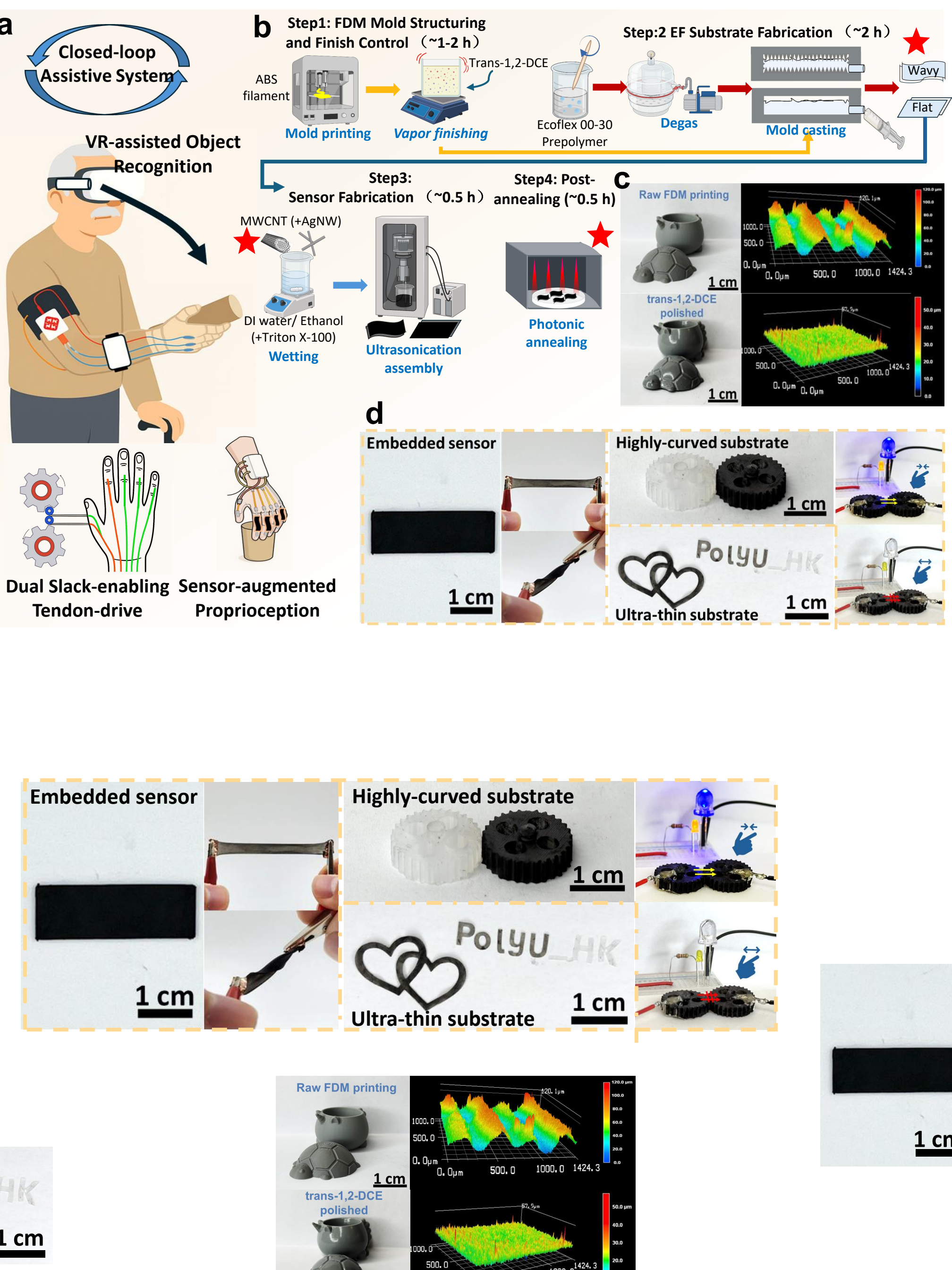

2
ΔR/R0
Calibrated finger flexion angle (°)
Index
Middle
Ring
Pinky
Finger

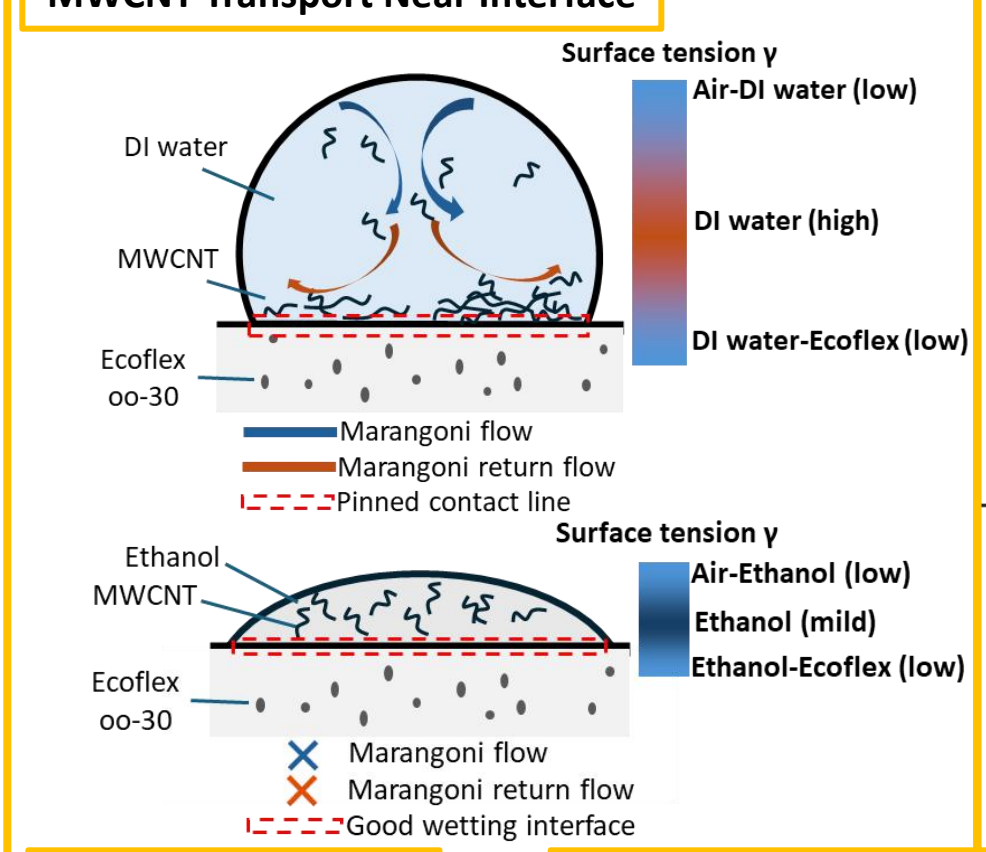

3
ΔR/R0
Calibrated finger flexion angle (°)
Index
Middle
Ring
Pinky
Finger

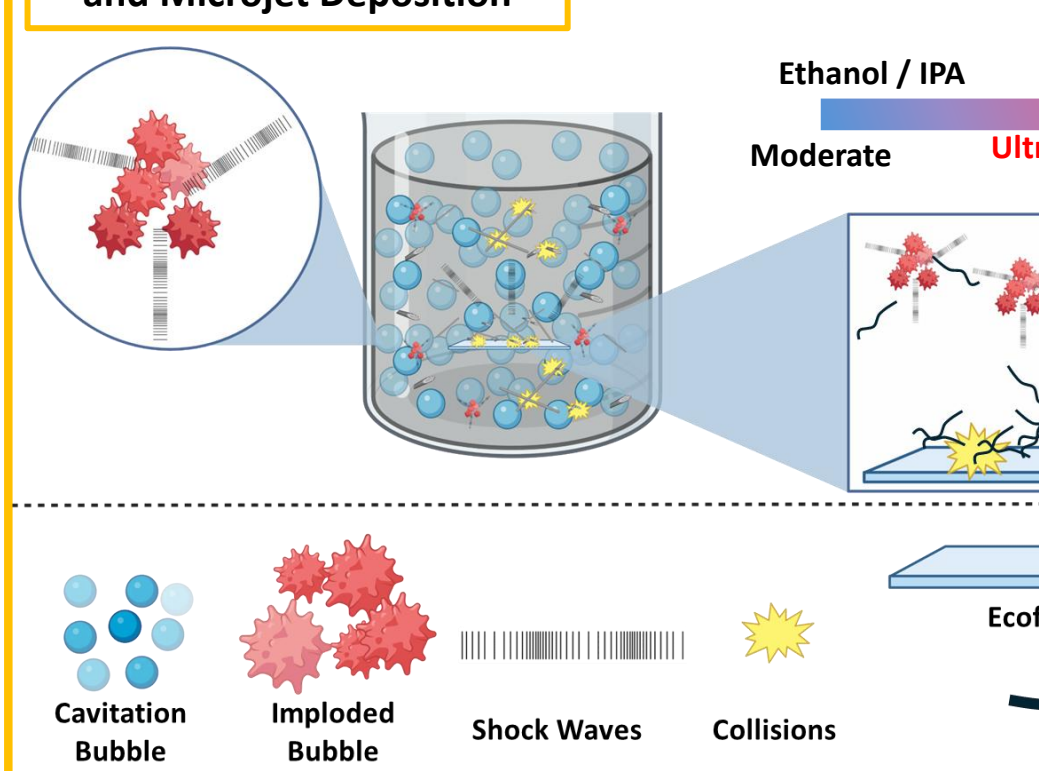

4
ΔR/R0
Calibrated finger flexion angle (°)
Index
Middle
Ring
Pinky
Finger


Strain-to-failure (%)
900
720
540
360
180
0
MWCNT@EF (Flat)
MWCNT@EF
(Wavy+Annealed)
Toughness
(MJ m^{-3})
3
2
1
0
Steady-state conductivity (S/m)
200
150
100
50
0
'uage factor'
80
60
40
20
0
-unstable
2000
1500
1000
500
0

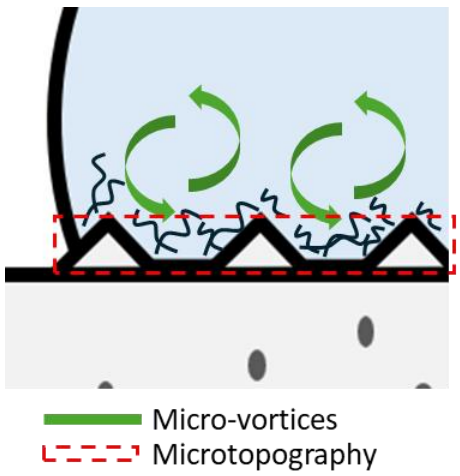

b
Cycle-to-unstable
6000
5000
4000
3000
2000
1000
Ultrasonication-based deposit
Other solution-based depositi
This work
Corresponding strain (%)
0
50
100
150
200
250
300
350
Fig
0
50
100
150
200
250


a
Closed-loop Assistive System
VR-assisted Object Recognition
Dual Slack-enabling Tendon-drive
Sensor-augmented Proprioception
b
Step1: FDM Mold Structuring and Finish Control （~1-2 h）
ABS filament
Mold printing
Trans-1,2-DCE
Vapor finishing
Step:2 EF Substrate Fabrication （~2 h）
Ecoflex 00-30 Prepolymer
Degas
Mold casting
Wavy
Flat
Step3: Sensor Fabrication （~0.5 h）
MWCNT (+AgNW)
DI water/ Ethanol (+Triton X-100)
Wetting
Ultrasonication assembly
Step4: Post-annealing (~0.5 h)
Photonic annealing
c
Raw FDM printing
1 cm
trans-1,2-DCE polished
1 cm
d
Embedded sensor
1 cm
Highly-curved substrate
1 cm
Ultra-thin substrate
1 cm

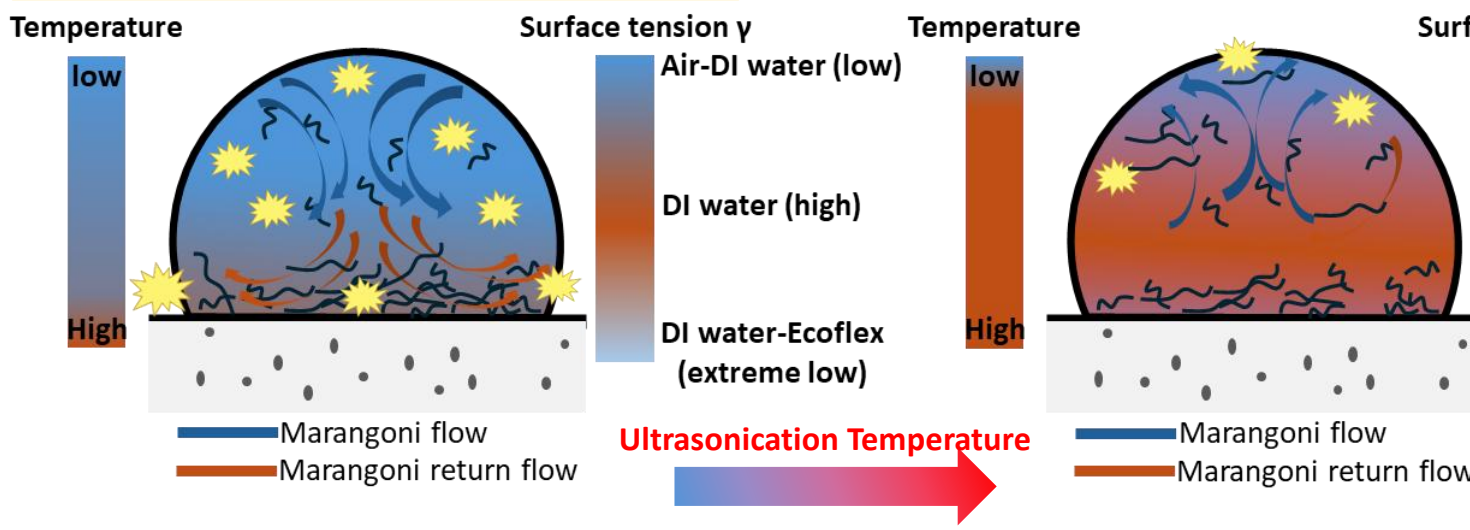


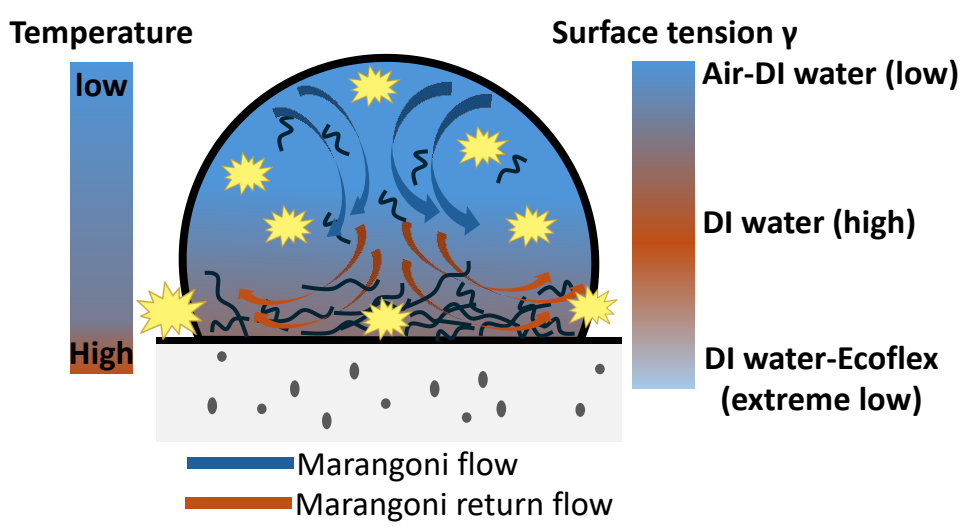


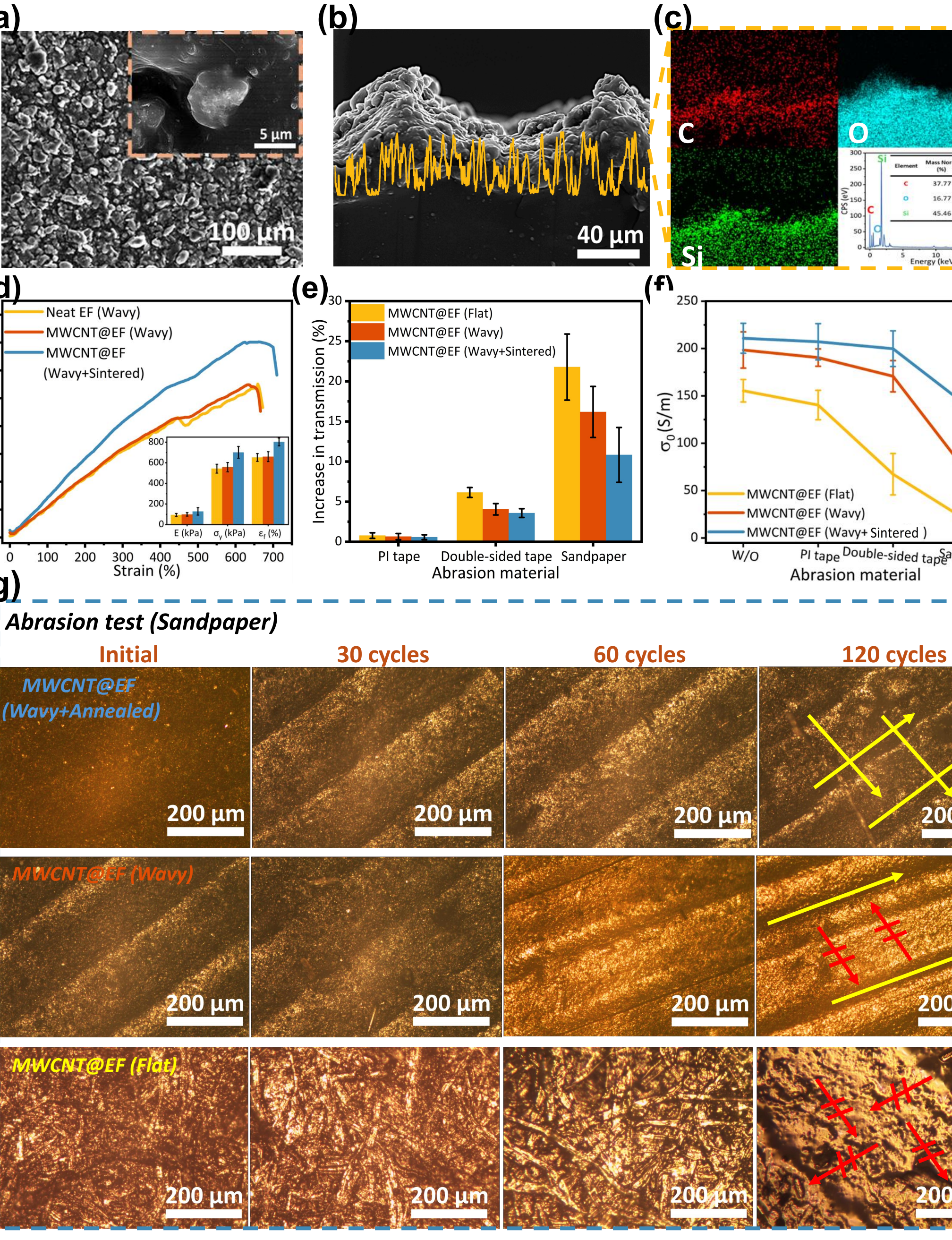
Surface Roughness v.s. Deposition

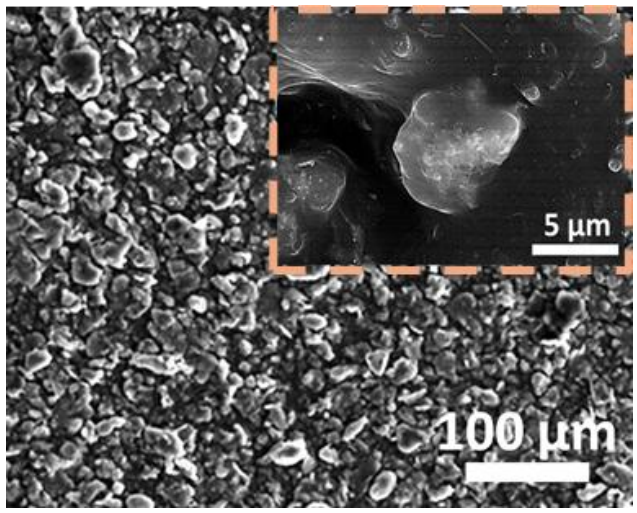


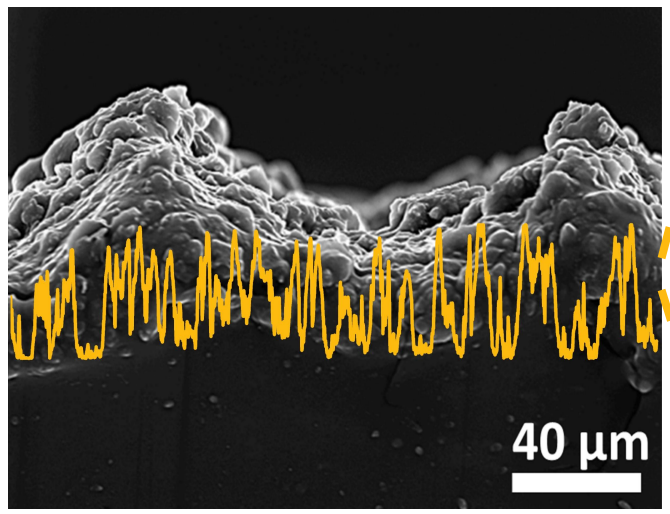
Thermal Gradient Modulation of Flow Fields and Shock Impacts

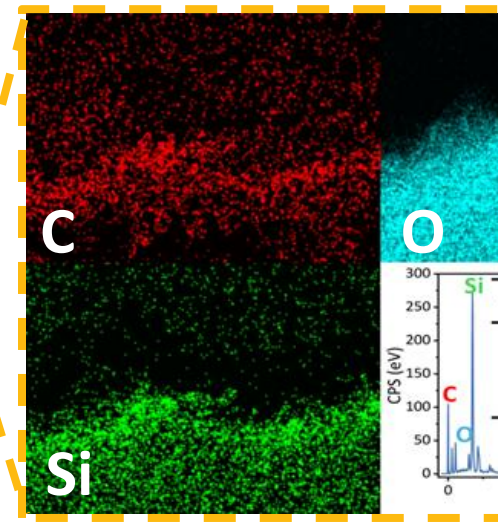


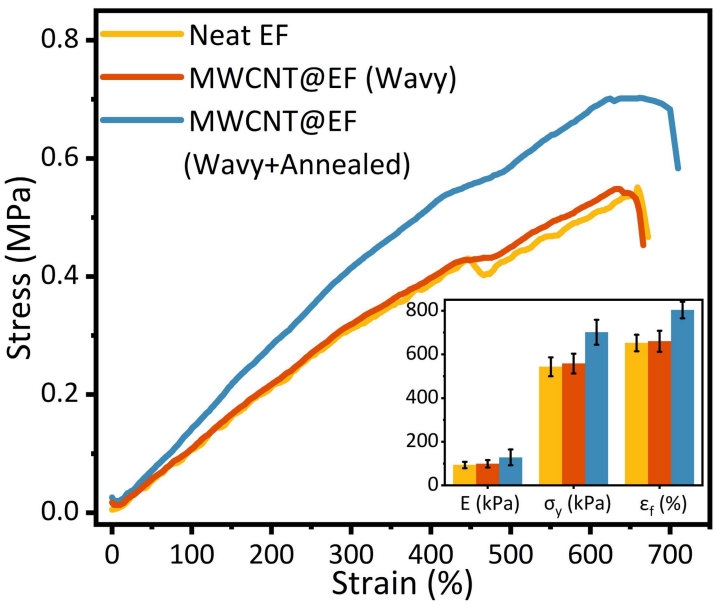


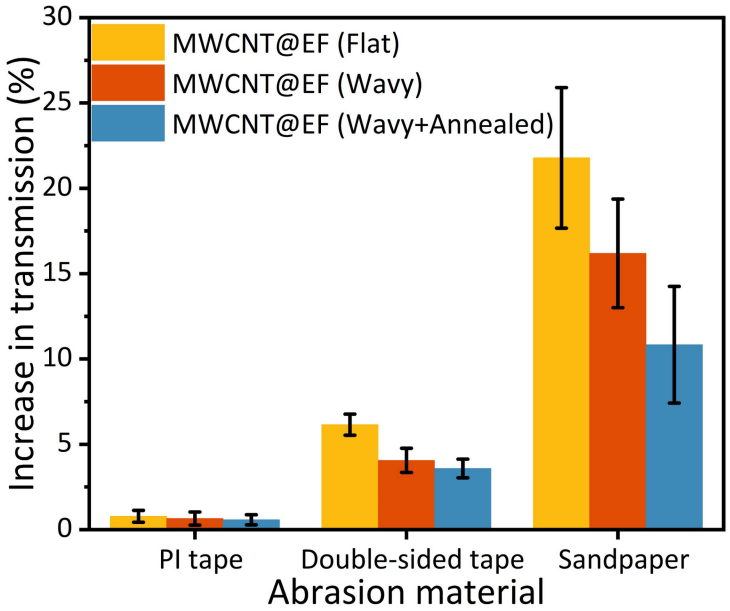

a)
5 µm
100 µm
(b)
40 µm
(c)
C
O
Si
Element
Mass Nor (%)
C 37.77
O 16.77
Si 45.46
CPS (eV)
Energy (keV)
d)
Neat EF (Wavy)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+Sintered)
E (kPa)
σy (kPa)
εf (%)
Strain (%)
(e)
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+Sintered)
Increase in transmission (%)
PI tape
Double-sided tape
Sandpaper
Abrasion material
(f)
σ0 (S/m)
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+ Sintered)
W/O
PI tape
Double-sided tape
Abrasion material
g)
Abrasion test (Sandpaper)
Initial
30 cycles
60 cycles
120 cycles
MWCNT@EF (Wavy+Annealed)
MWCNT@EF (Wavy)
MWCNT@EF (Flat)
200 µm

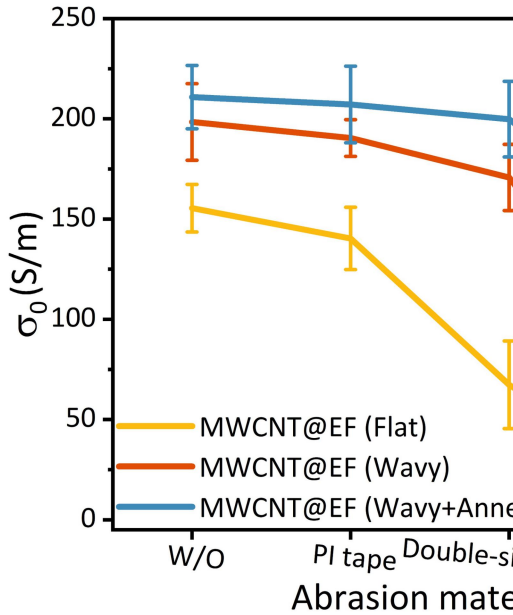




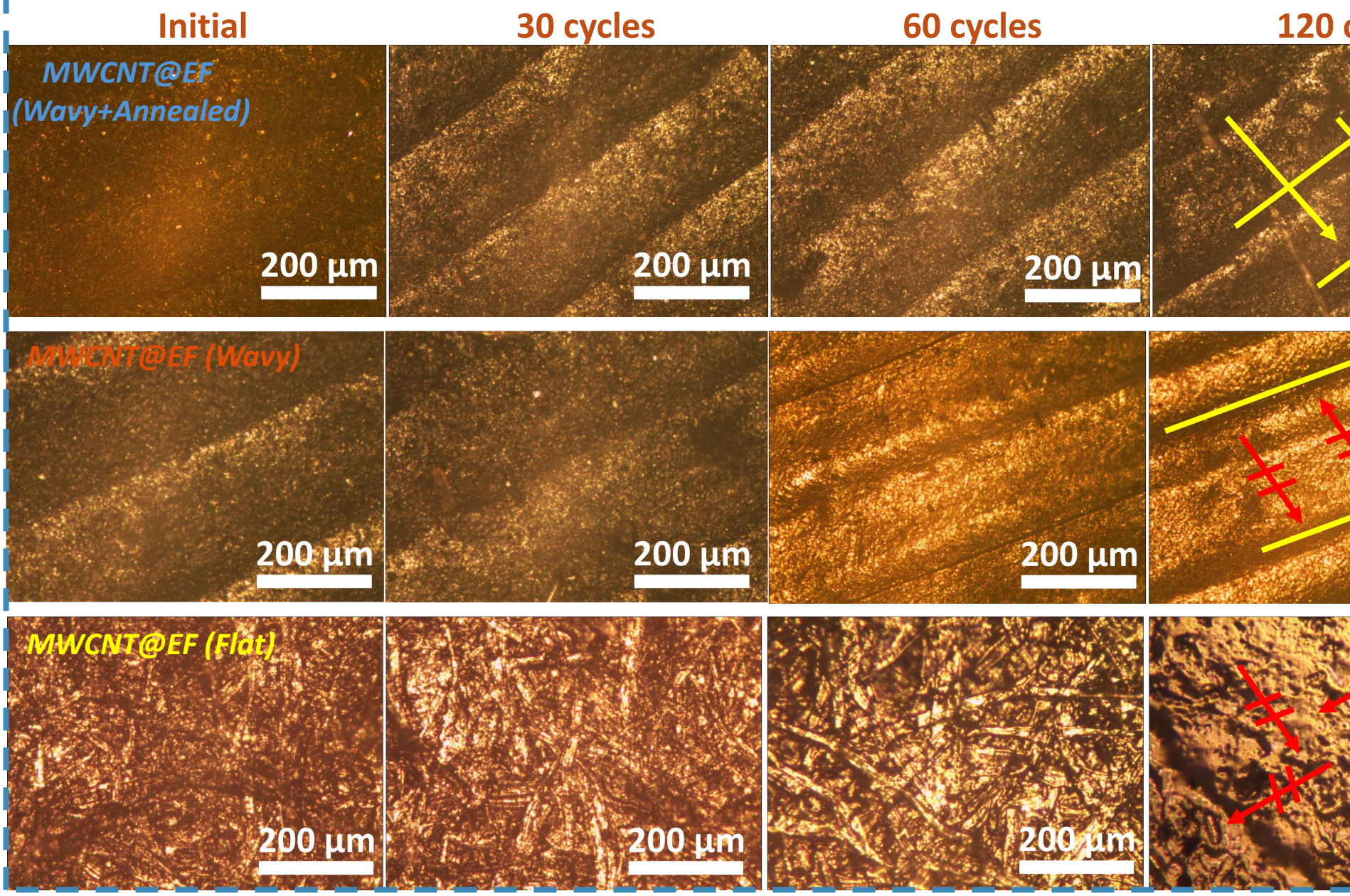


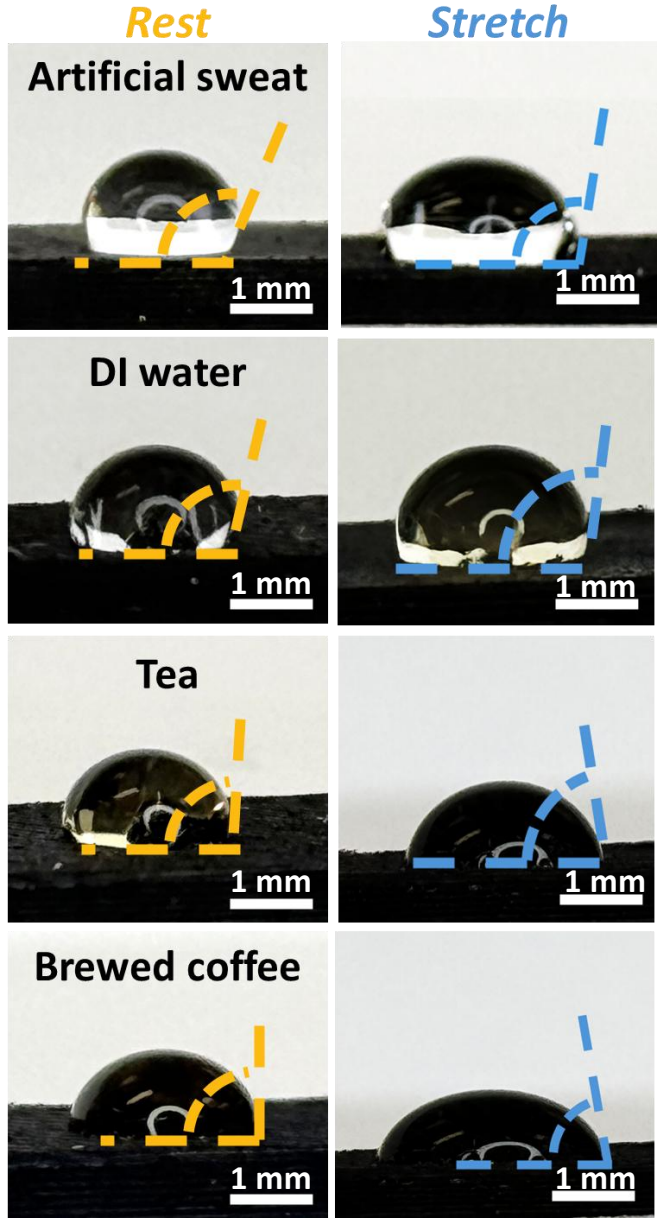


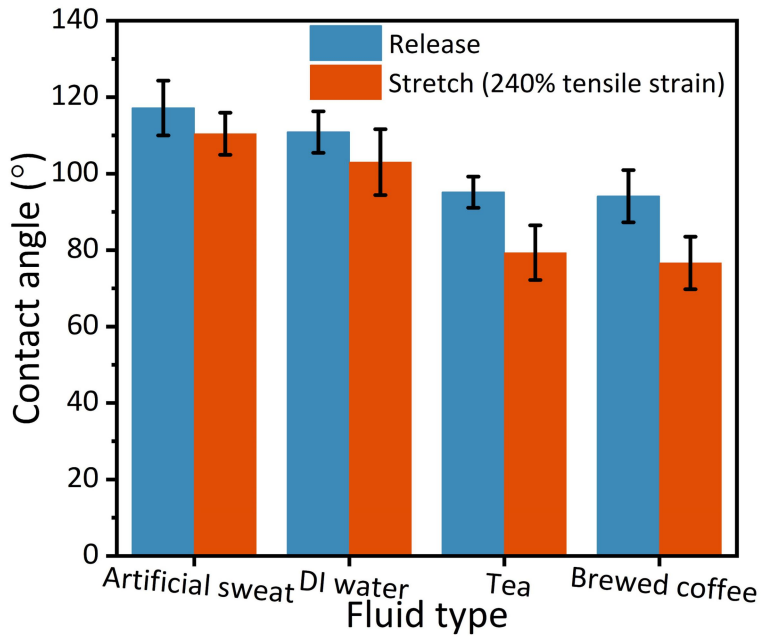


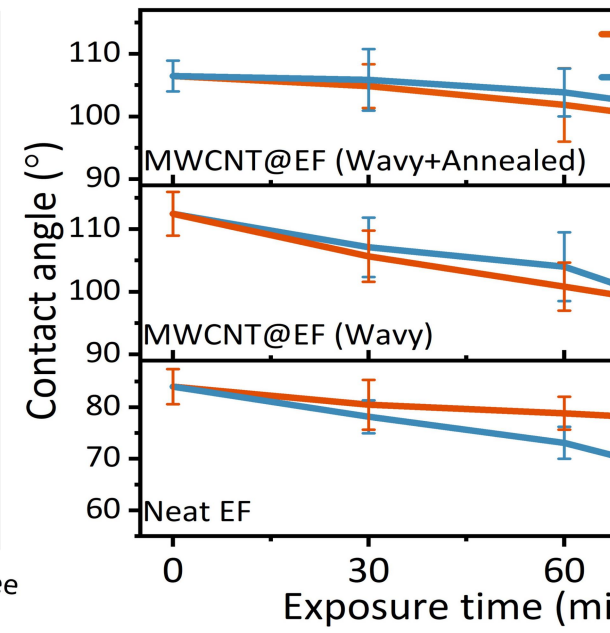


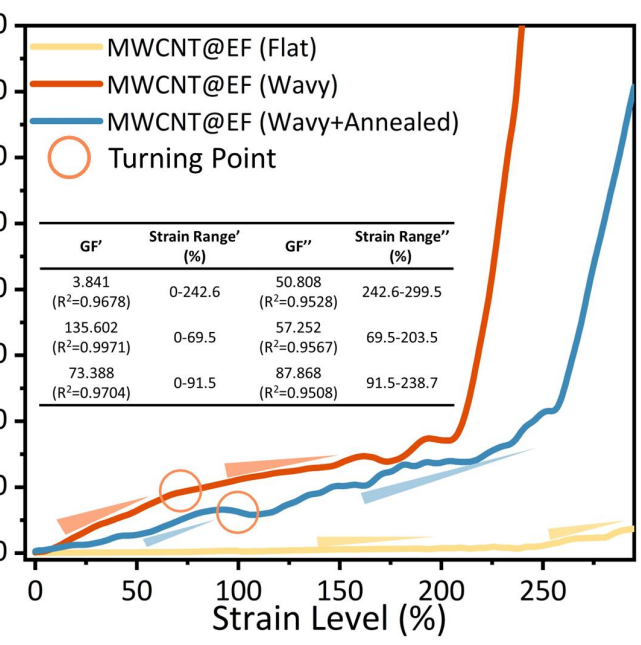
Abrasion test (Sandpaper)



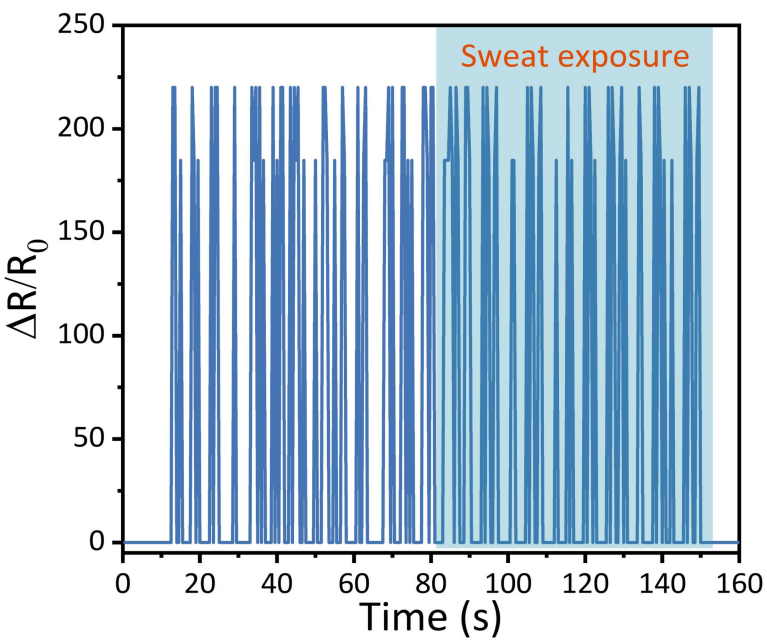


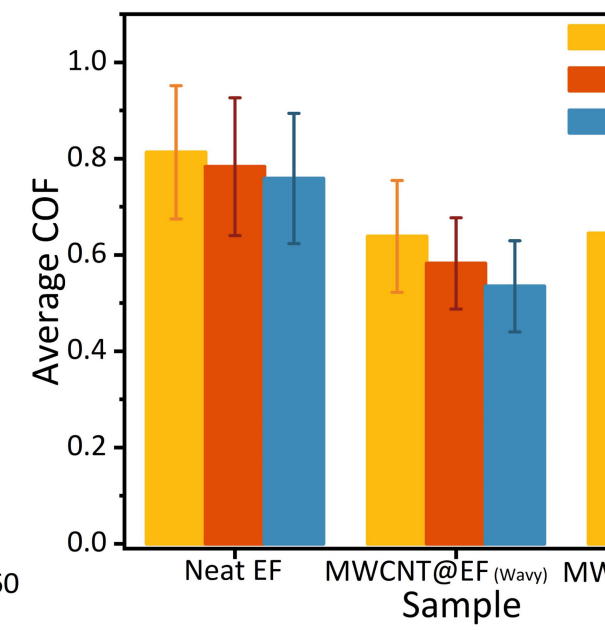


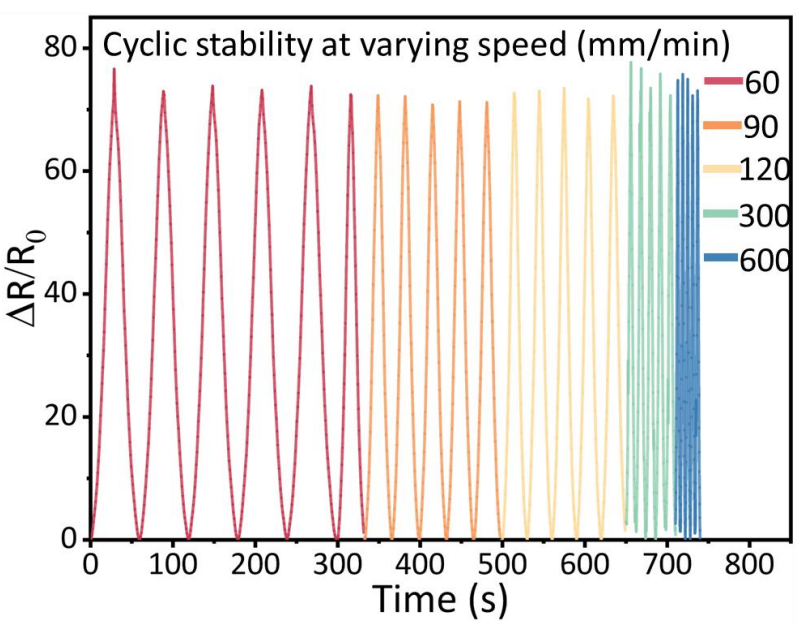


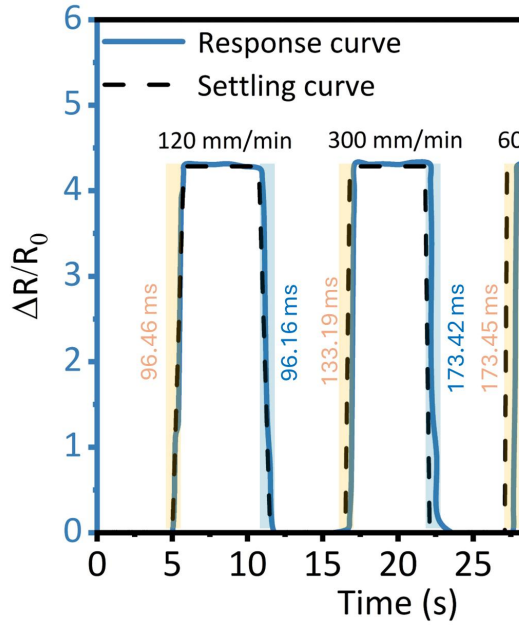


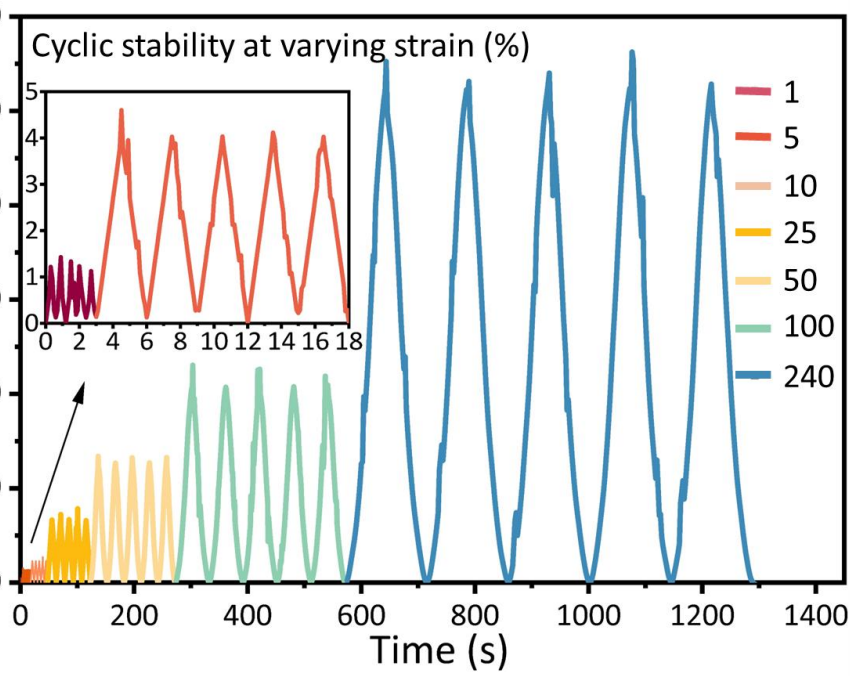
GF'	Strain Range' (%)	GF''	Strain Range'' (%)
3.841 (R^2=0.9678)	0-242.6	50.808 (R^2=0.9528)	242.6-299.5
135.602 (R^2=0.9971)	0-69.5	57.252 (R^2=0.9567)	69.5-203.5
73.388 (R^2=0.9704)	0-91.5	87.868 (R^2=0.9508)	91.5-238.7

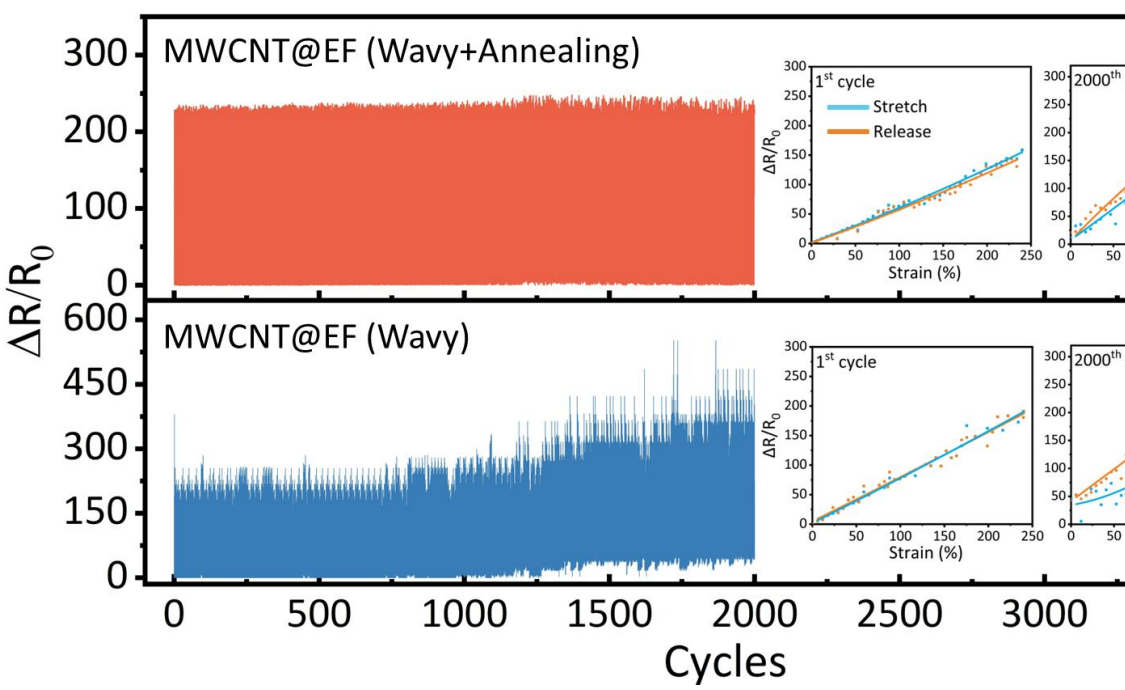


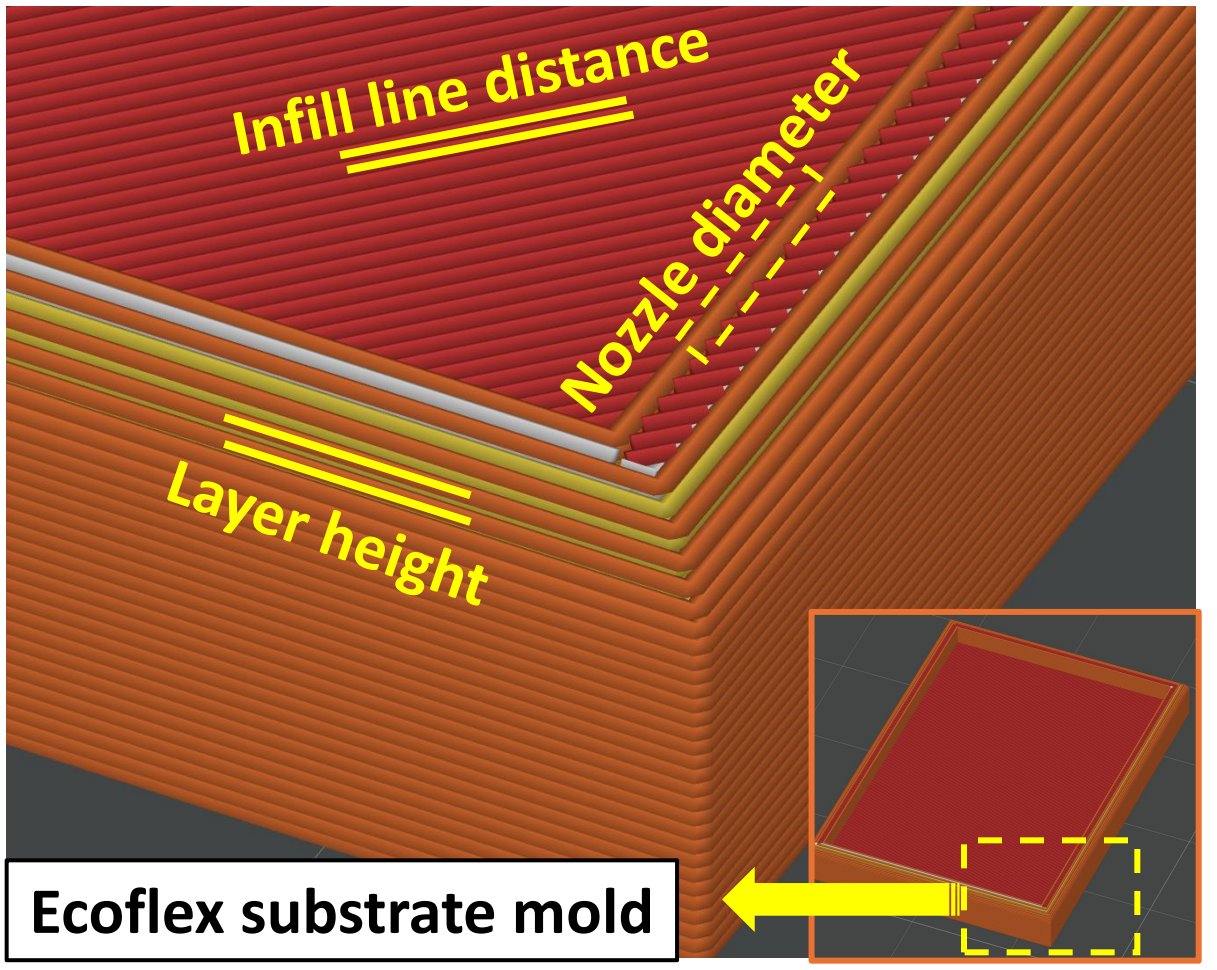


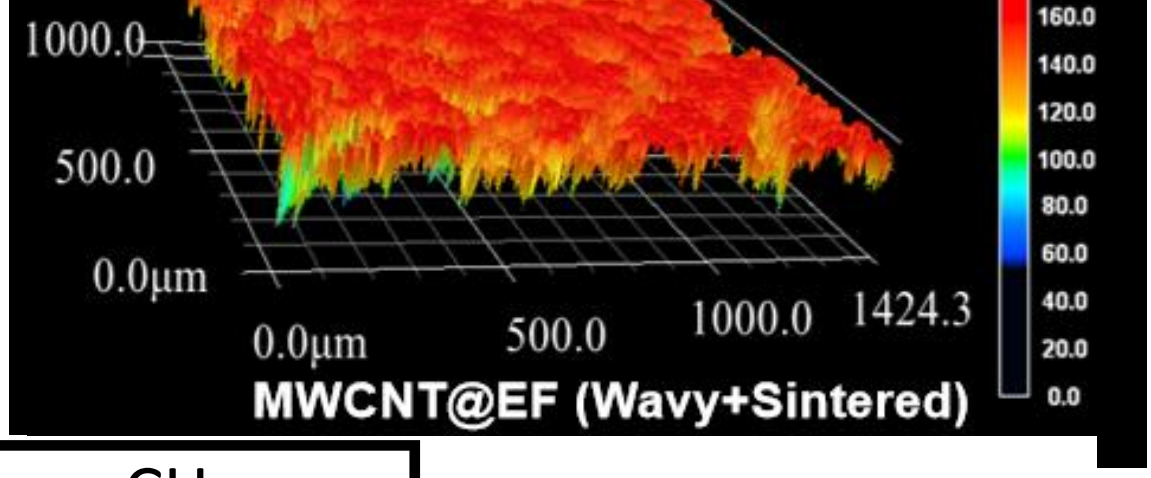


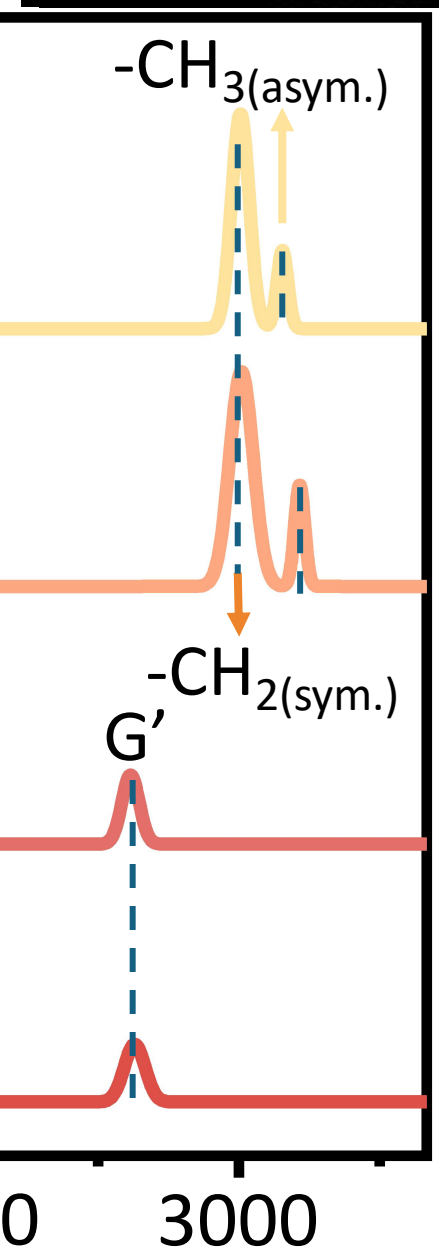




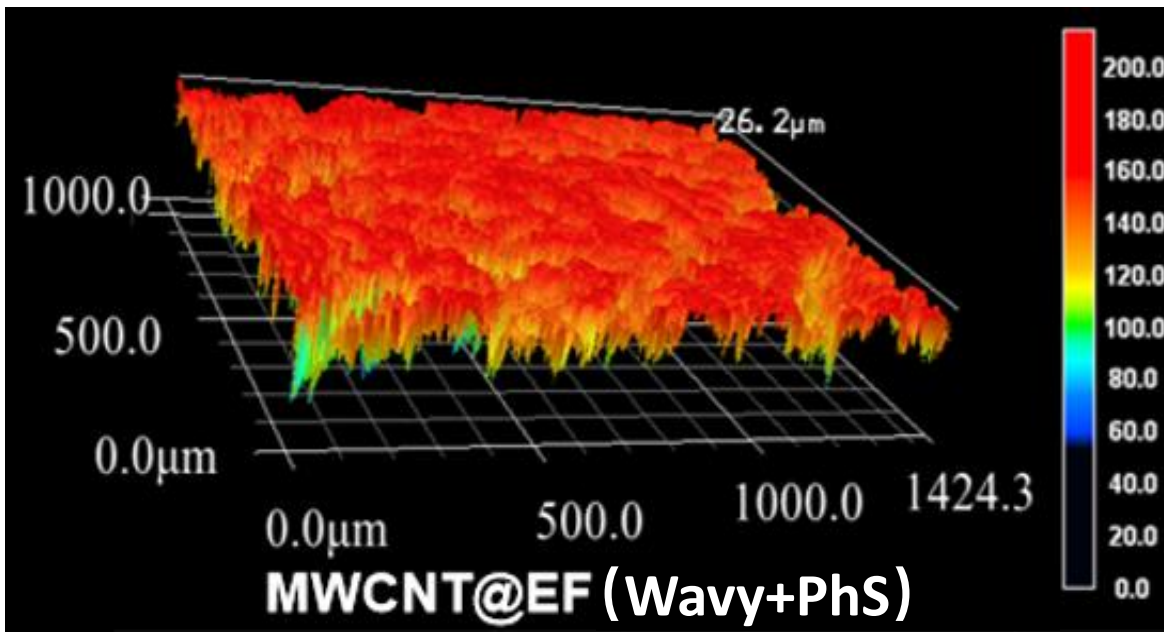


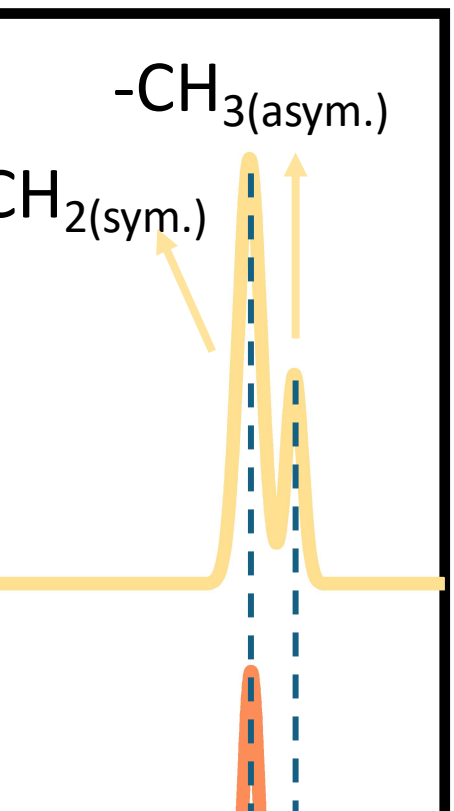

Infill line distance
Nozzle diameter
Layer height
Ecoflex substrate mold

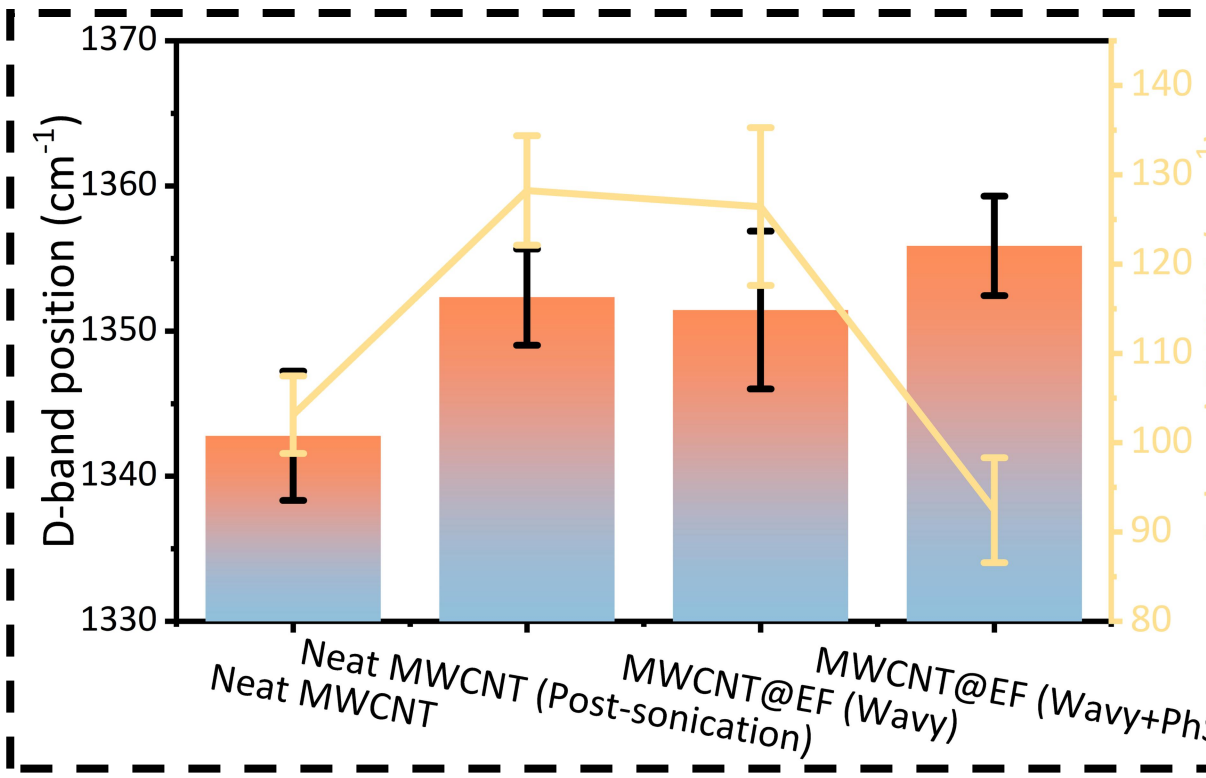

1000.0
500.0
0.0µm
0.0µm
500.0
1000.0
1424.3
MWCNT@EF (Wavy+Sintered)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0

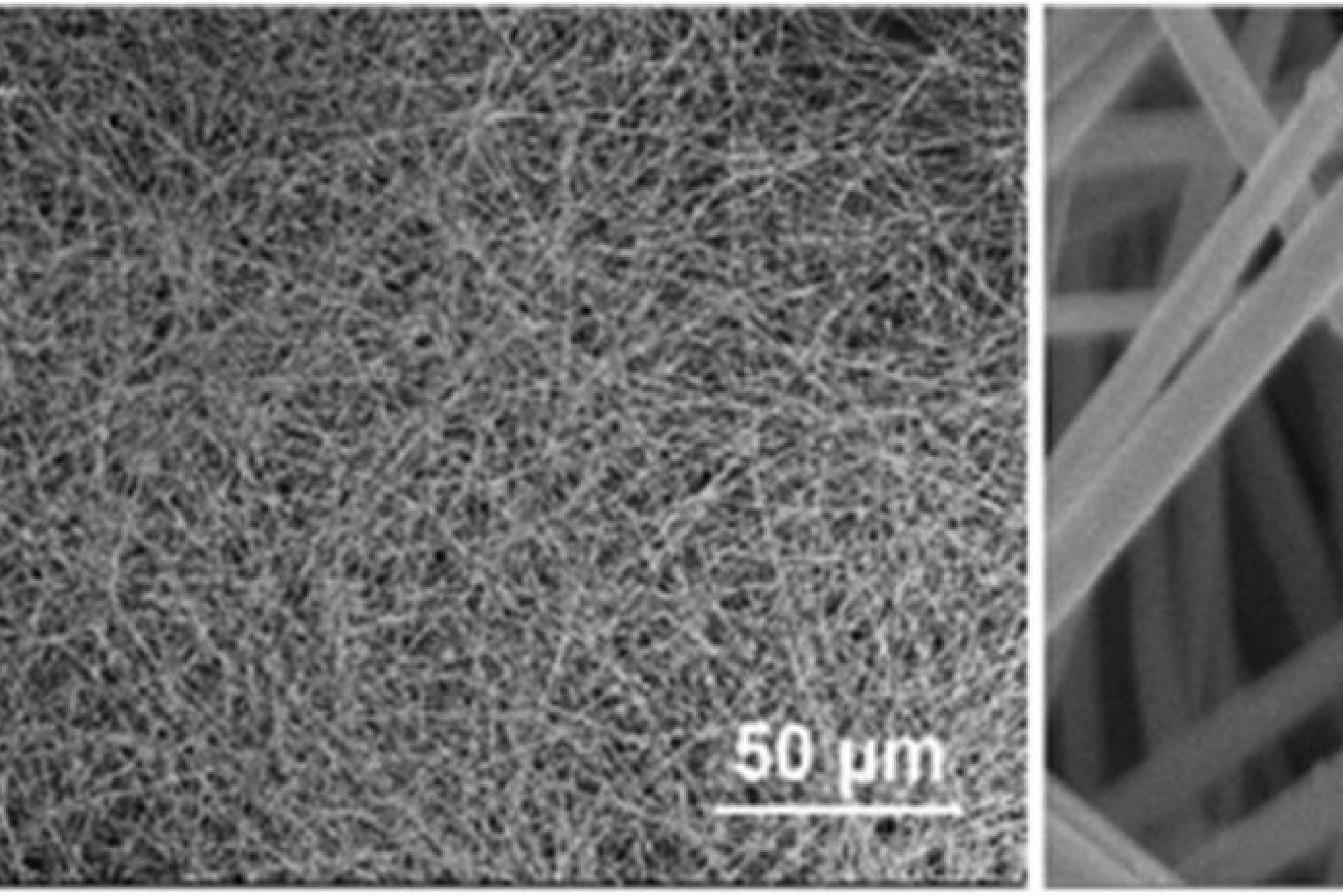

-CH3(asym.)
-CH2(sym.)
G'
0
3000

a

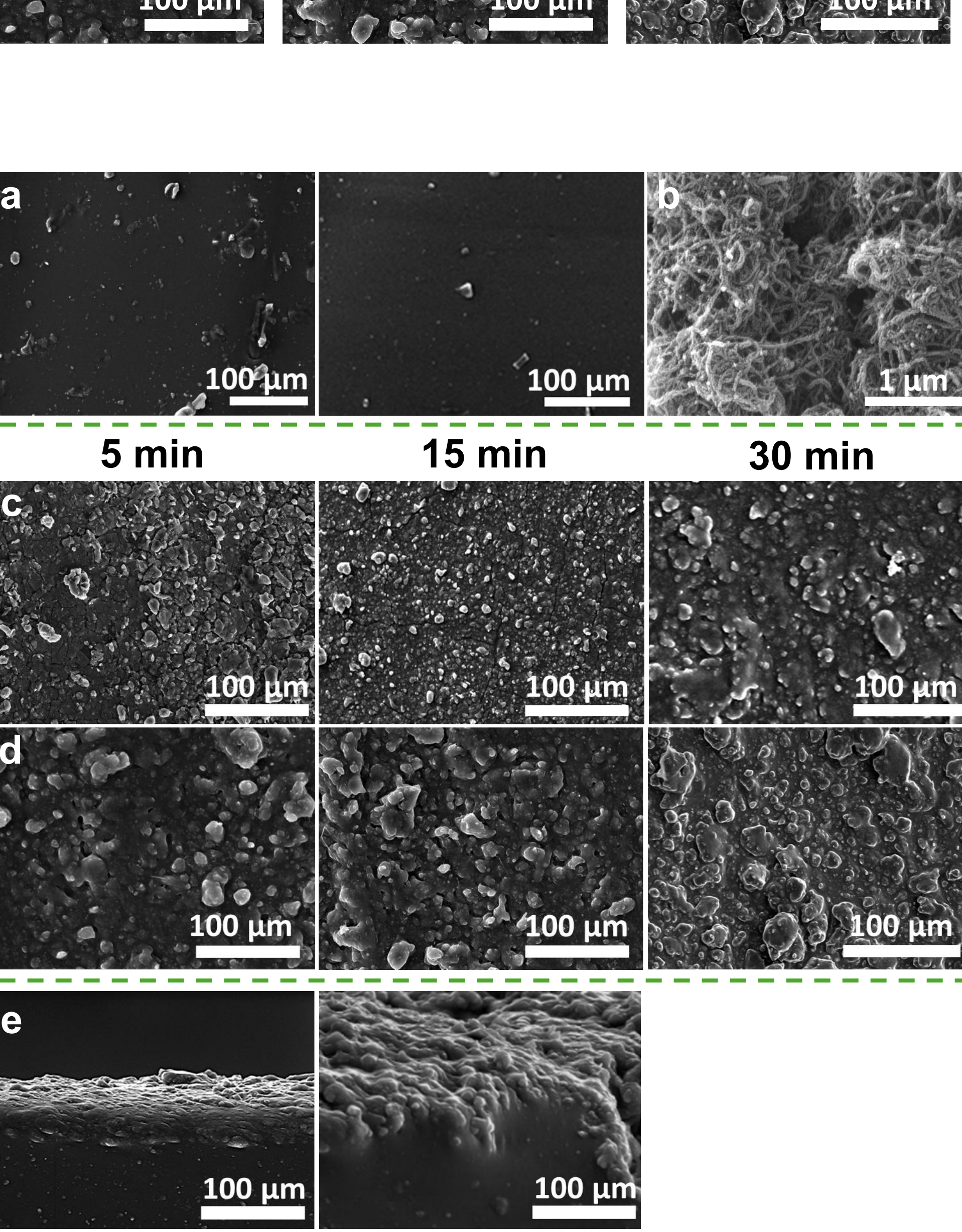

26.2µm
1000.0
500.0
0.0µm
0.0µm
500.0
1000.0
1424.3
MWCNT@EF (Wavy+PhS)
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0

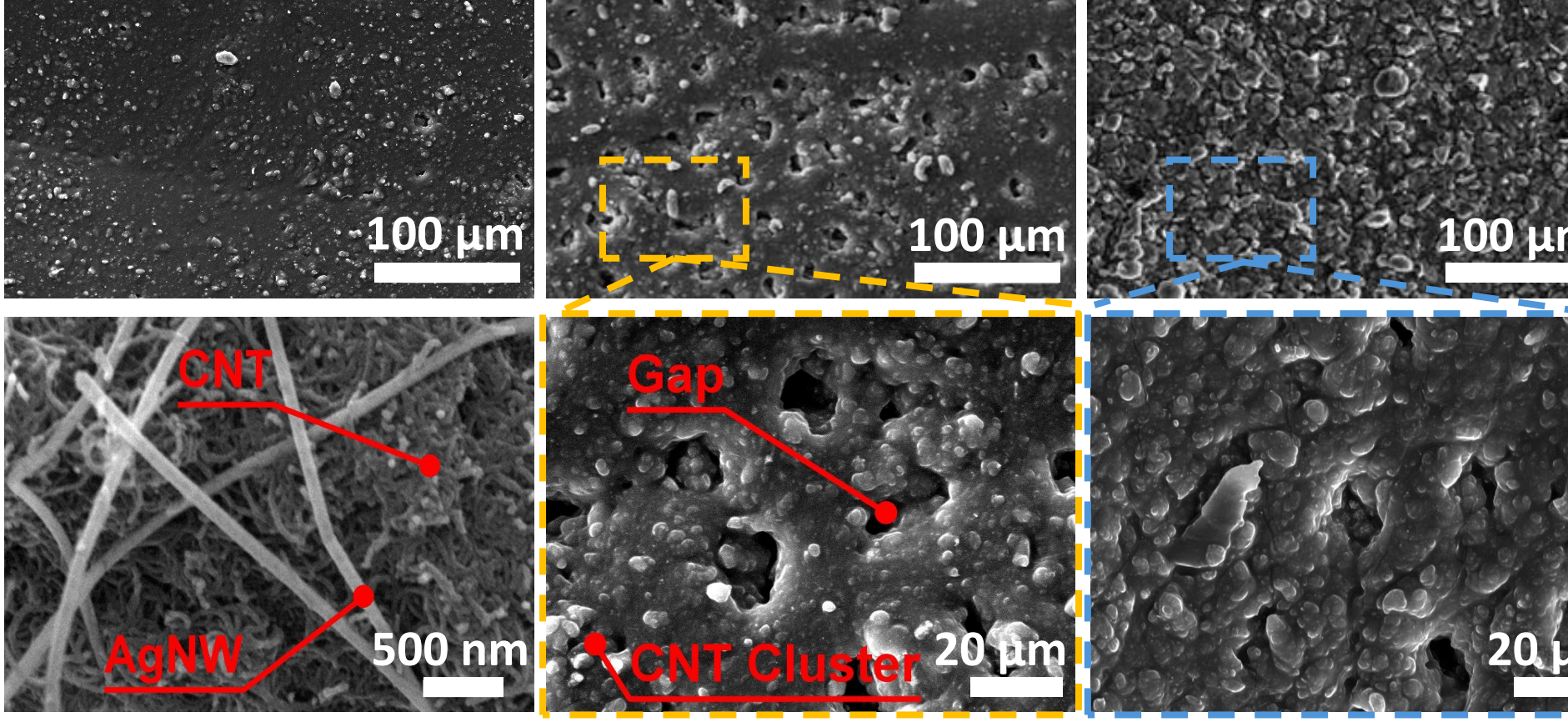

-CH3(asym.)
-CH2(sym.)

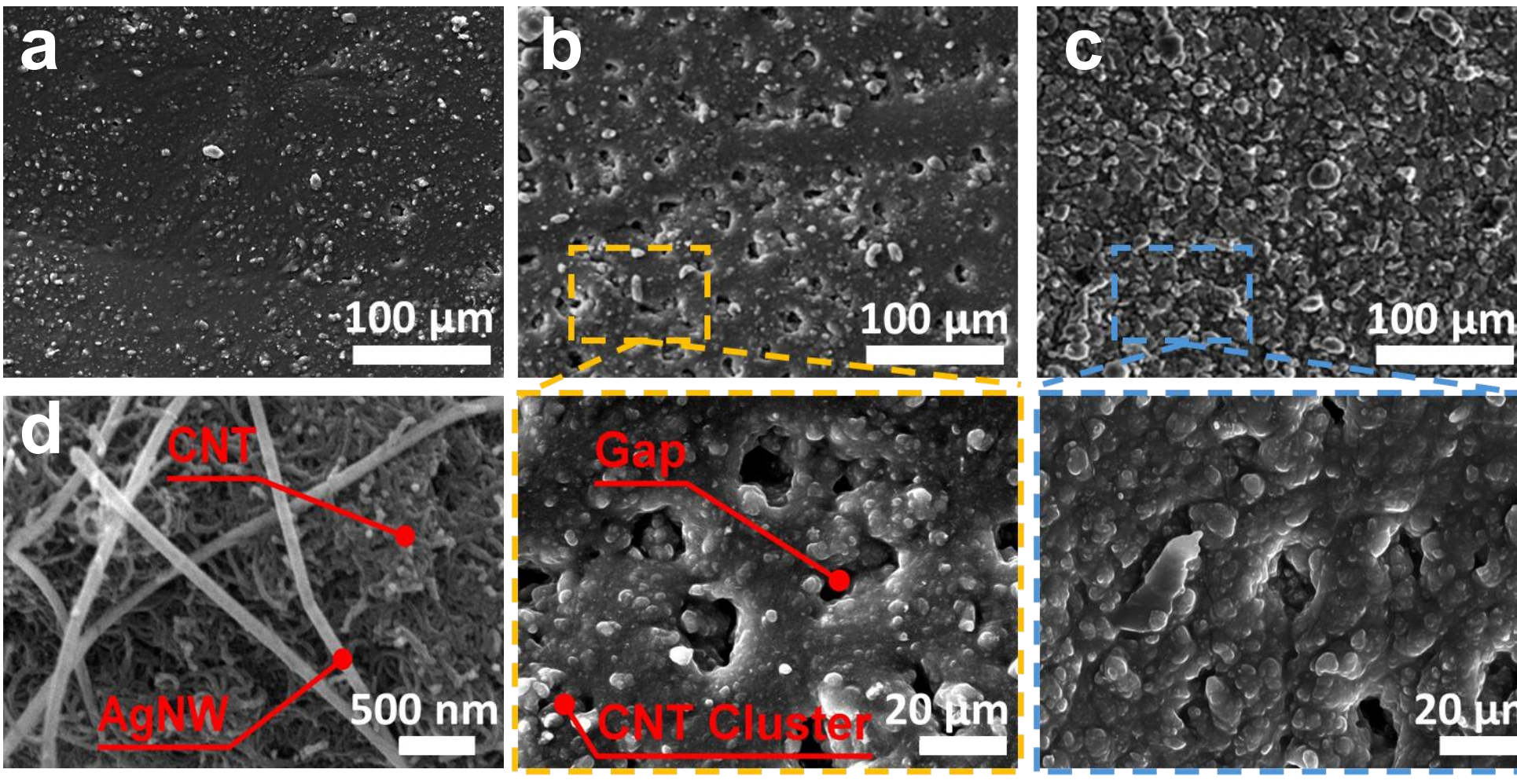

D-band position (cm-1)
1370
1360
1350
1340
1330
140
130
120
110
100
90
80
Neat MWCNT
Neat MWCNT (Post-sonication)
MWCNT@EF (Wavy)
MWCNT@EF (Wavy+Ph

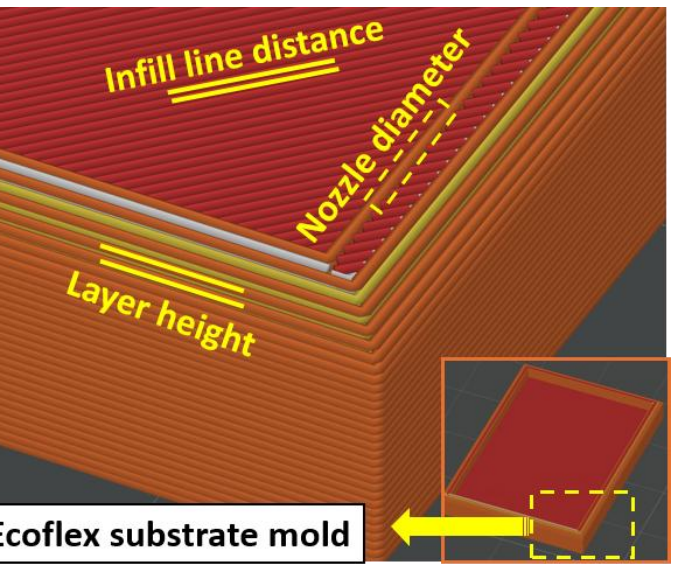


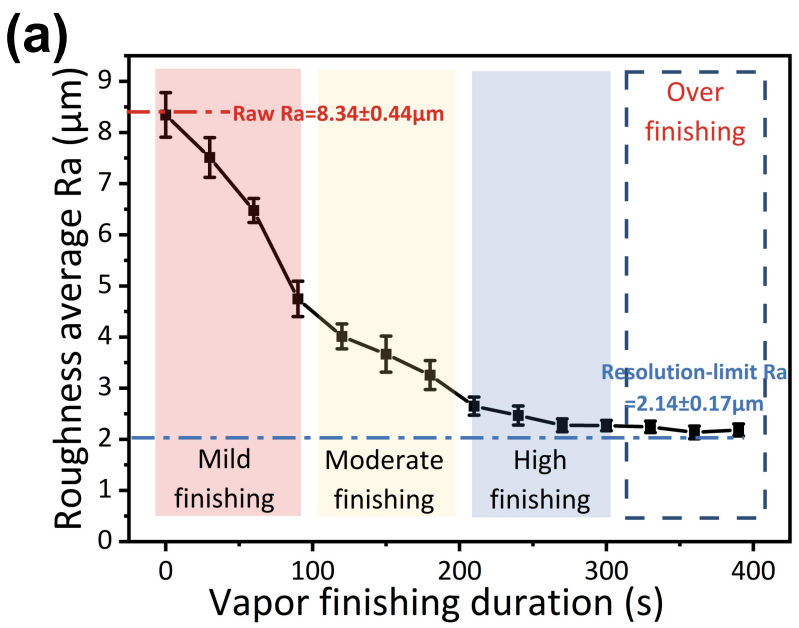
(a)

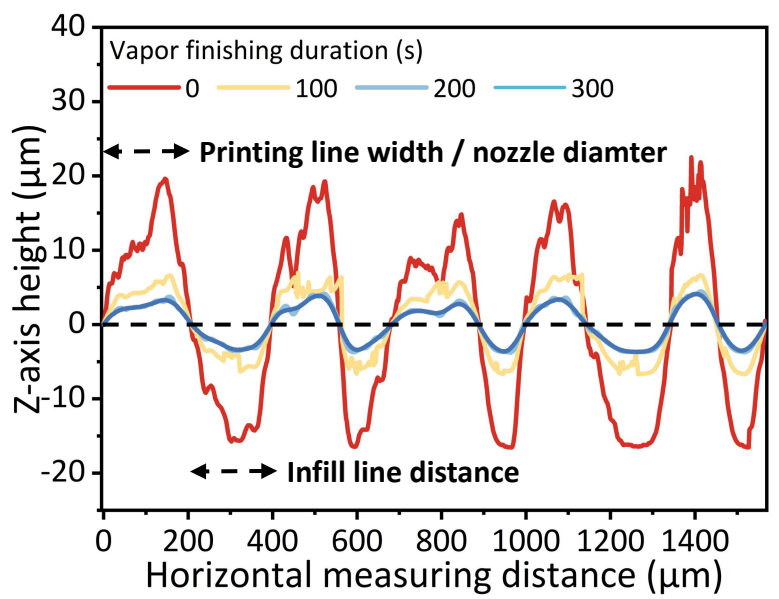

100 µm
100 µm
100 µm
a
100 µm
100 µm
b
1 µm
5 min
15 min
30 min
c
100 µm
100 µm
100 µm
d
100 µm
100 µm
100 µm
e
100 µm
100 µm

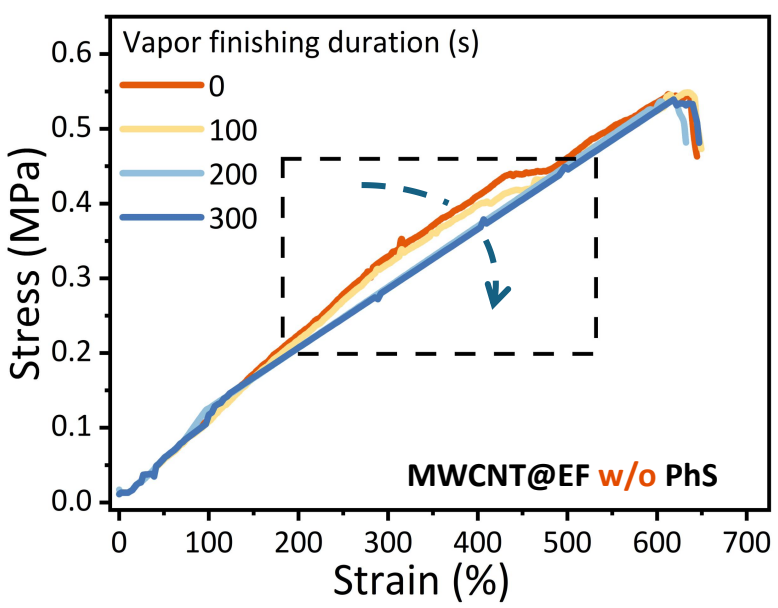

100 µm
100 µm
100 µm
CNT
AgNW
500 nm
Gap
CNT Cluster
20 µm
20 µm

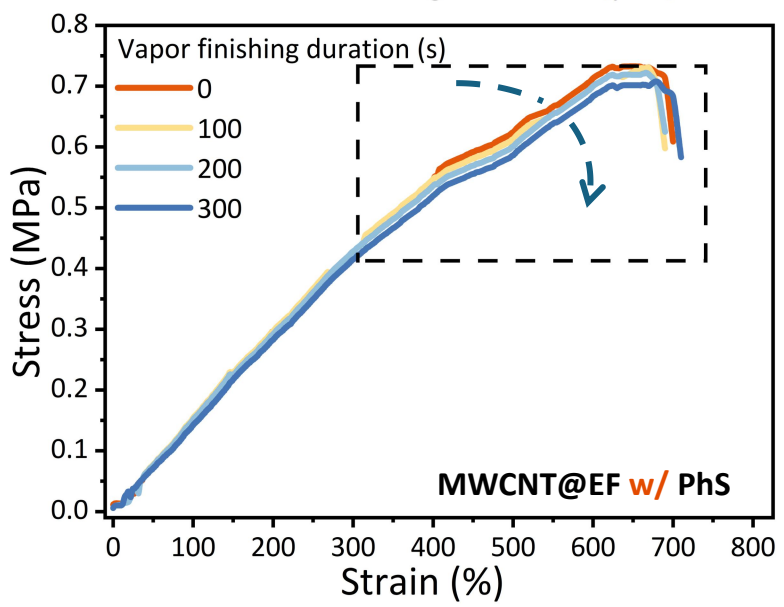

a
100 µm
b
100 µm
c
100 µm
d
CNT
AgNW
500 nm
Gap
CNT Cluster
20 µm
20 µm

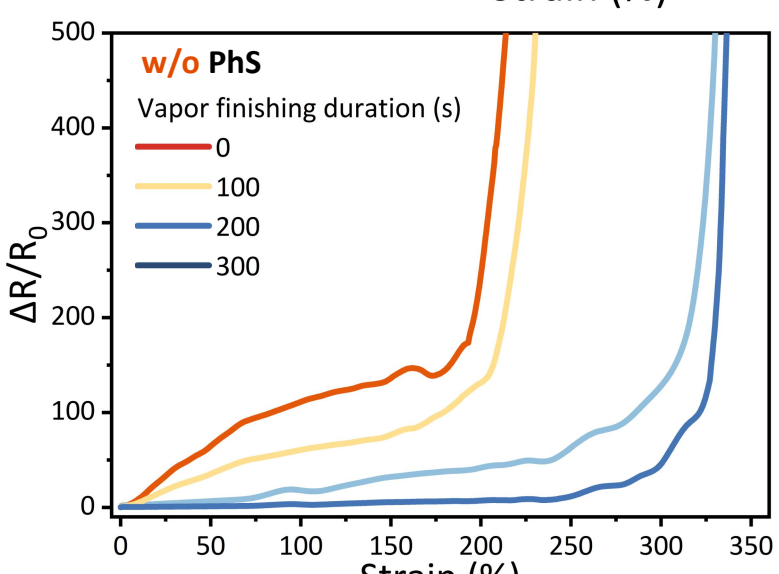

Infill line distance
Nozzle diameter
Layer height
Ecoflex substrate mold

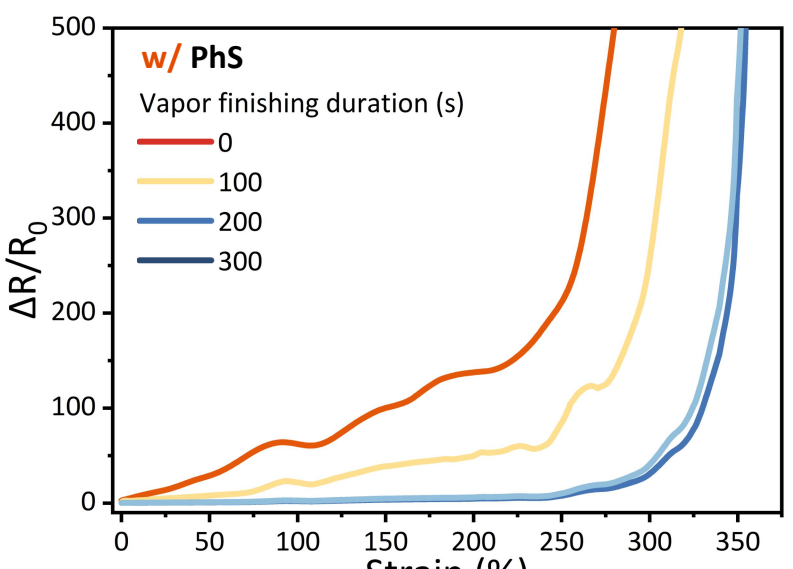

(a)
Raw Ra=8.34±0.44μm
Over finishing
Resolution-limit Ra =2.14±0.17μm
Mild finishing
Moderate finishing
High finishing
Roughness average Ra (μm)
Vapor finishing duration (s)


Vapor finishing duration (s)
0
100
200
300
Printing line width / nozzle diamter
Infill line distance
Z-axis height (μm)
Horizontal measuring distance (μm)

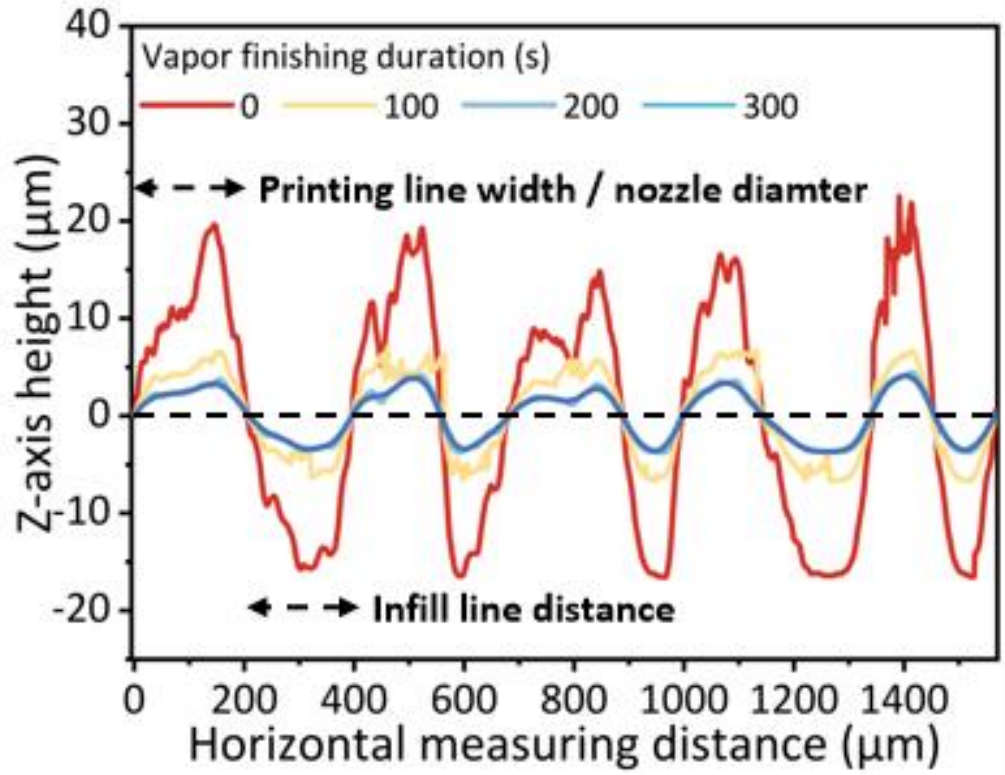

Vapor finishing duration (s)
0
100
200
300
MWCNT@EF w/o PhS
Stress (MPa)
Strain (%)

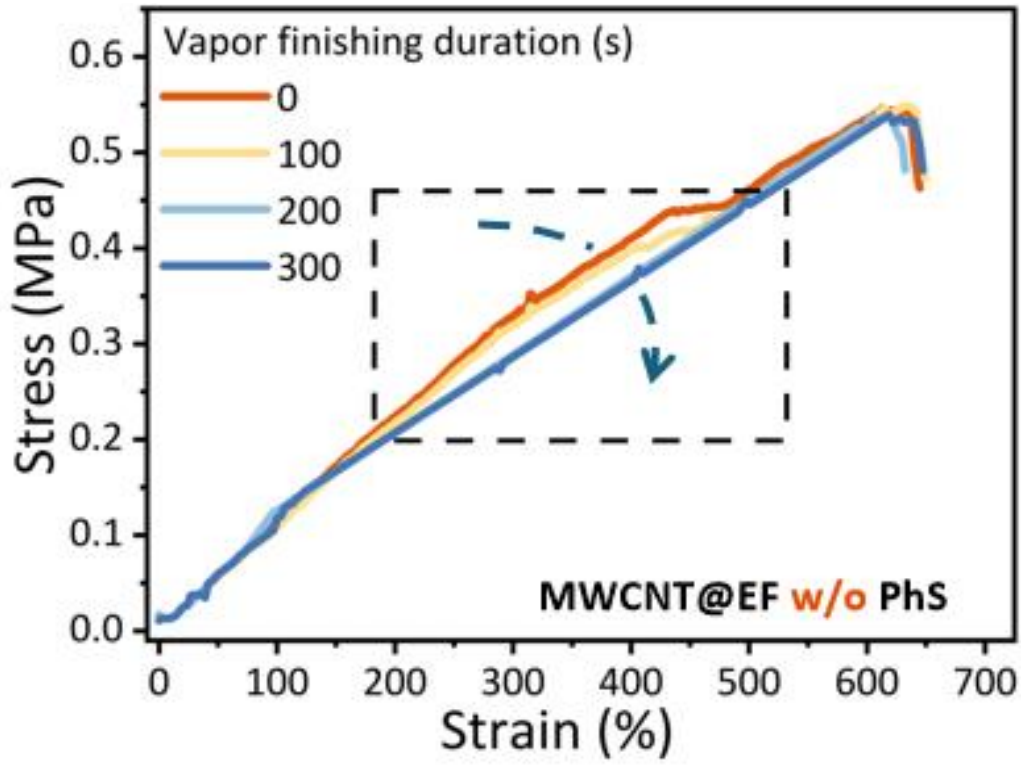

Vapor finishing duration (s)
0
100
200
300
MWCNT@EF w/ PhS
Stress (MPa)
Strain (%)

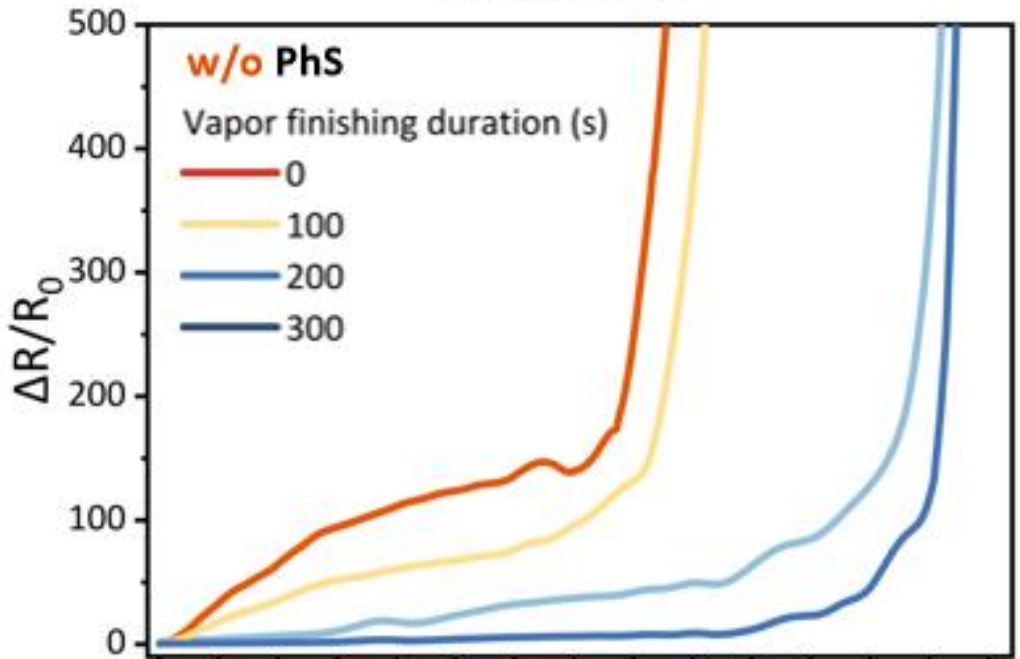

w/o PhS
Vapor finishing duration (s)
0
100
200
300
ΔR/R0

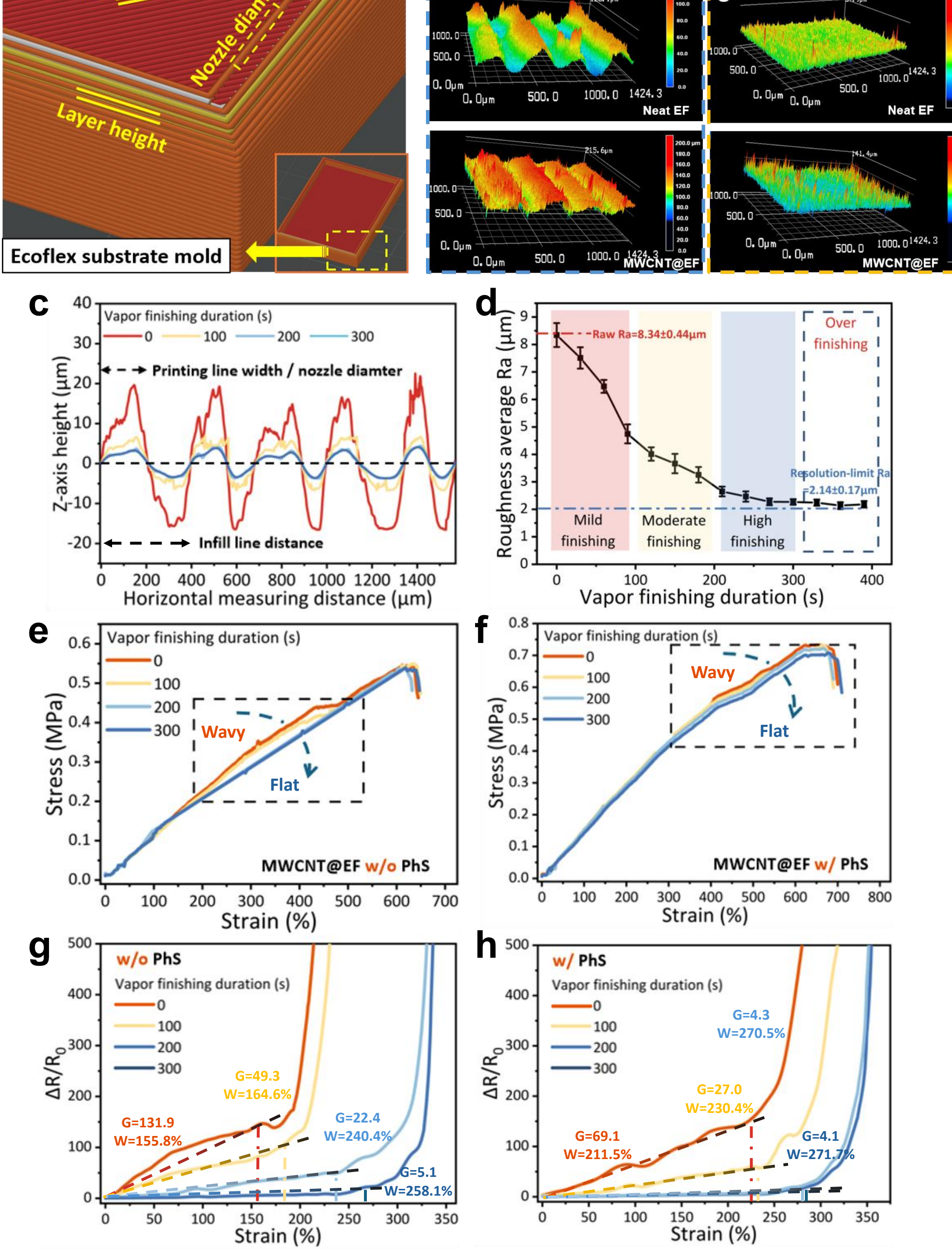

w/ PhS
Vapor finishing duration (s)
0
100
200
300
ΔR/R0

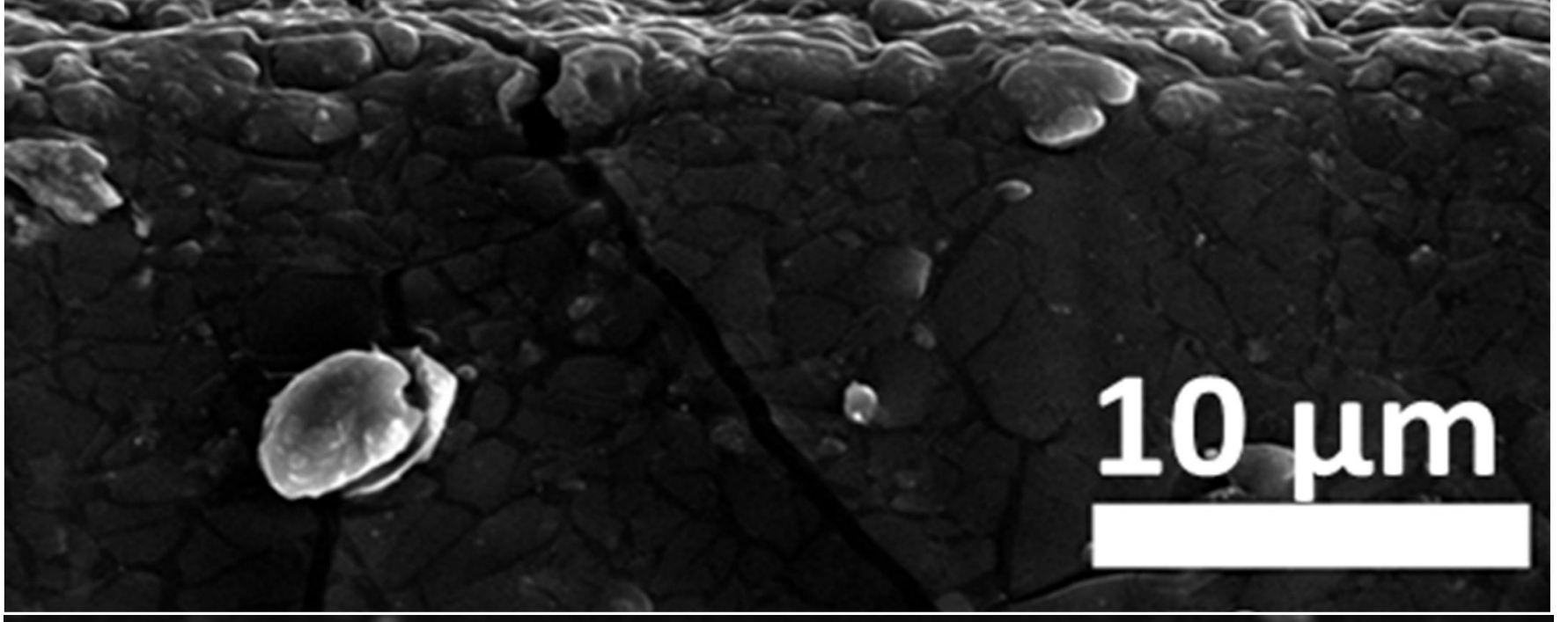
Ecoflex substrate mold
0. 0μm
0. 0μm

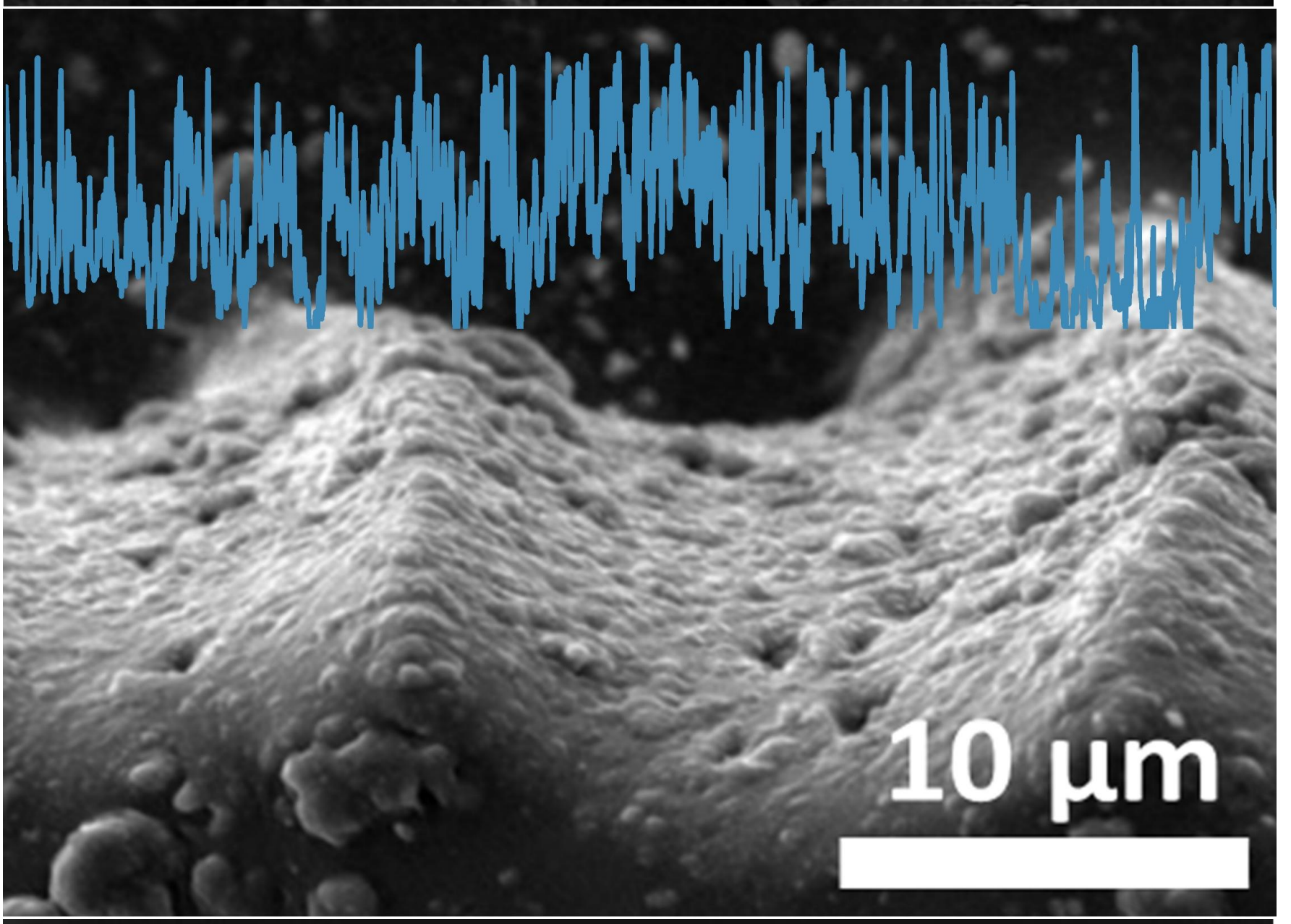

Vapor finishing duration (s)
0
100
200
300
Printing line width / nozzle diamter
Infill line distance
Z-axis height (μm)
Horizontal measuring distance (μm)

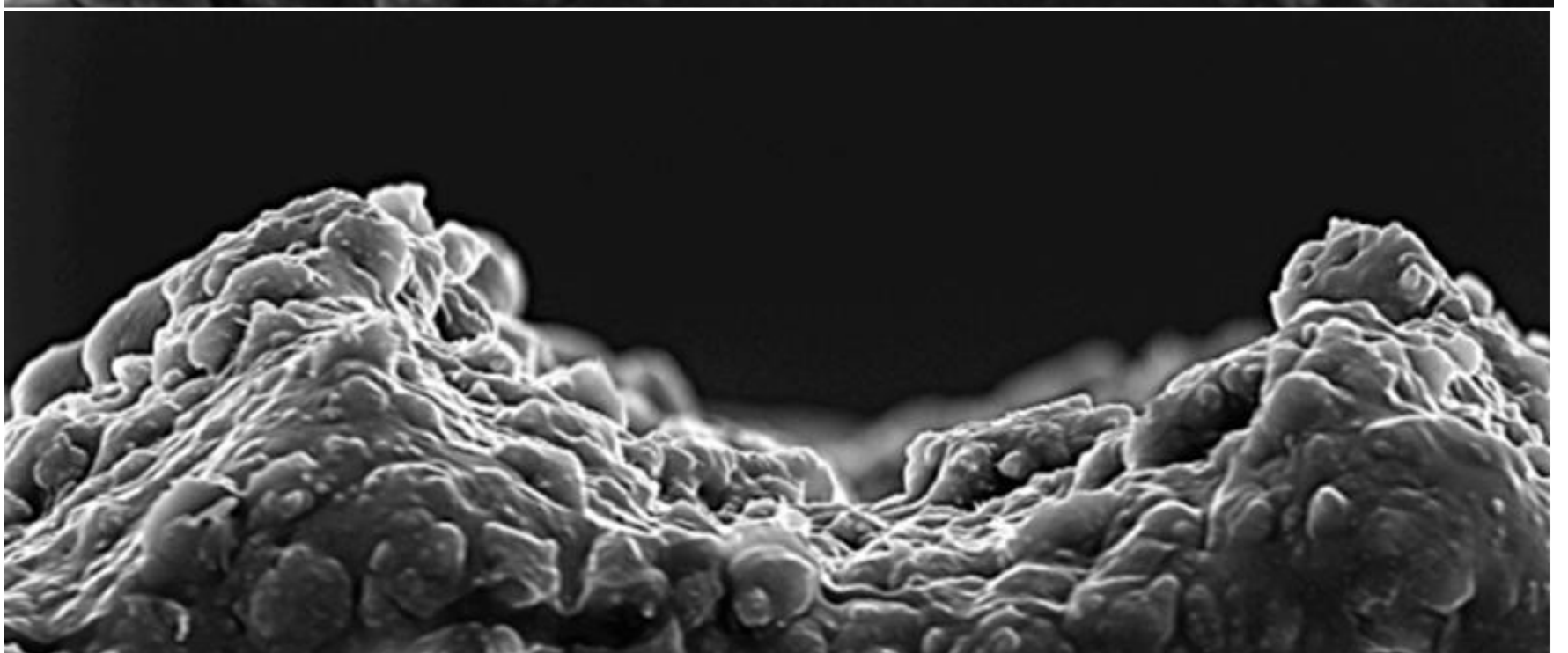

Vapor finishing duration (s)
0
100
200
300
MWCNT@EF w/o PhS
Stress (MPa)
Strain (%)

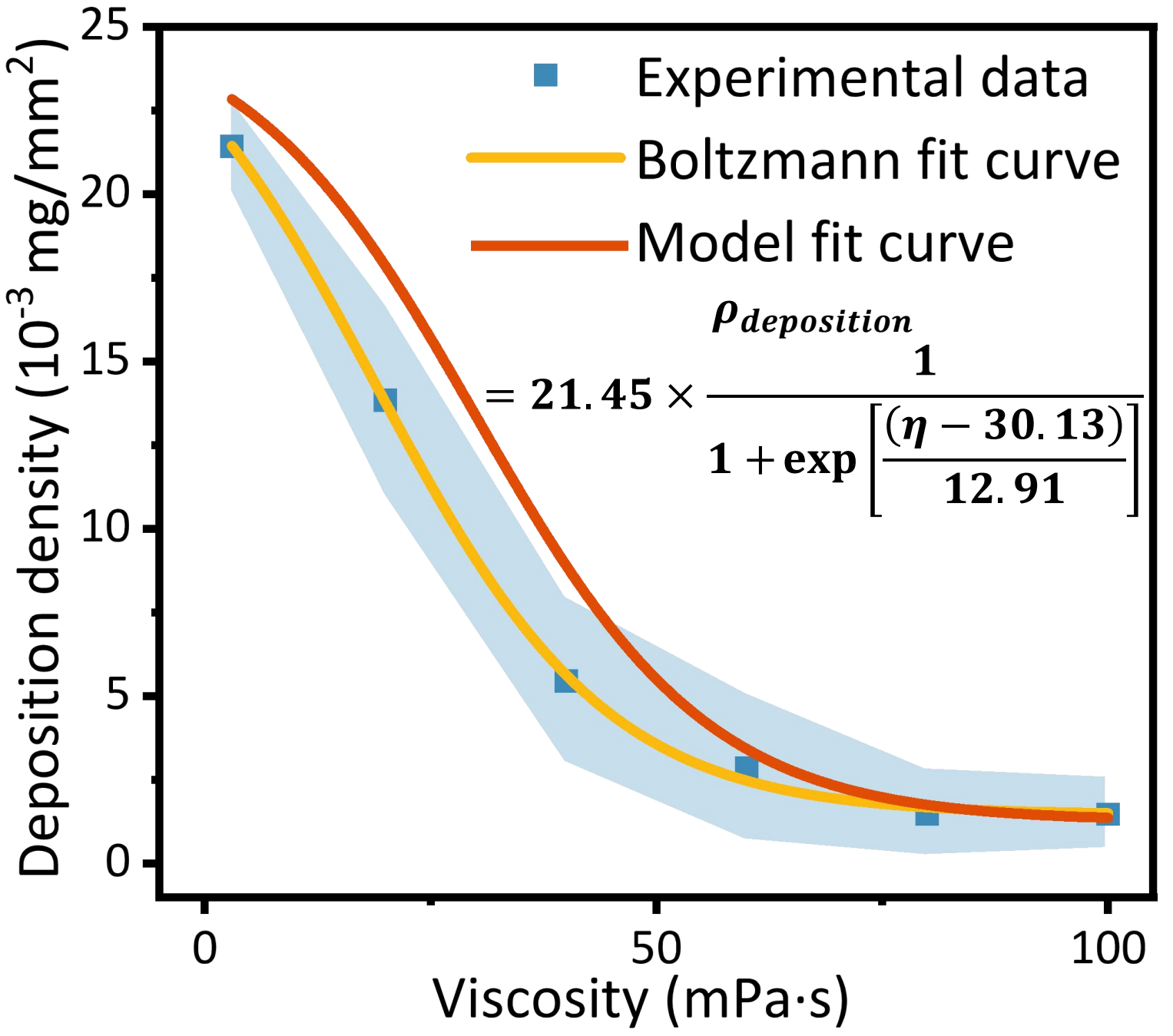

w/o PhS
Vapor finishing duration (s)
0
100
200
300
ΔR/R0

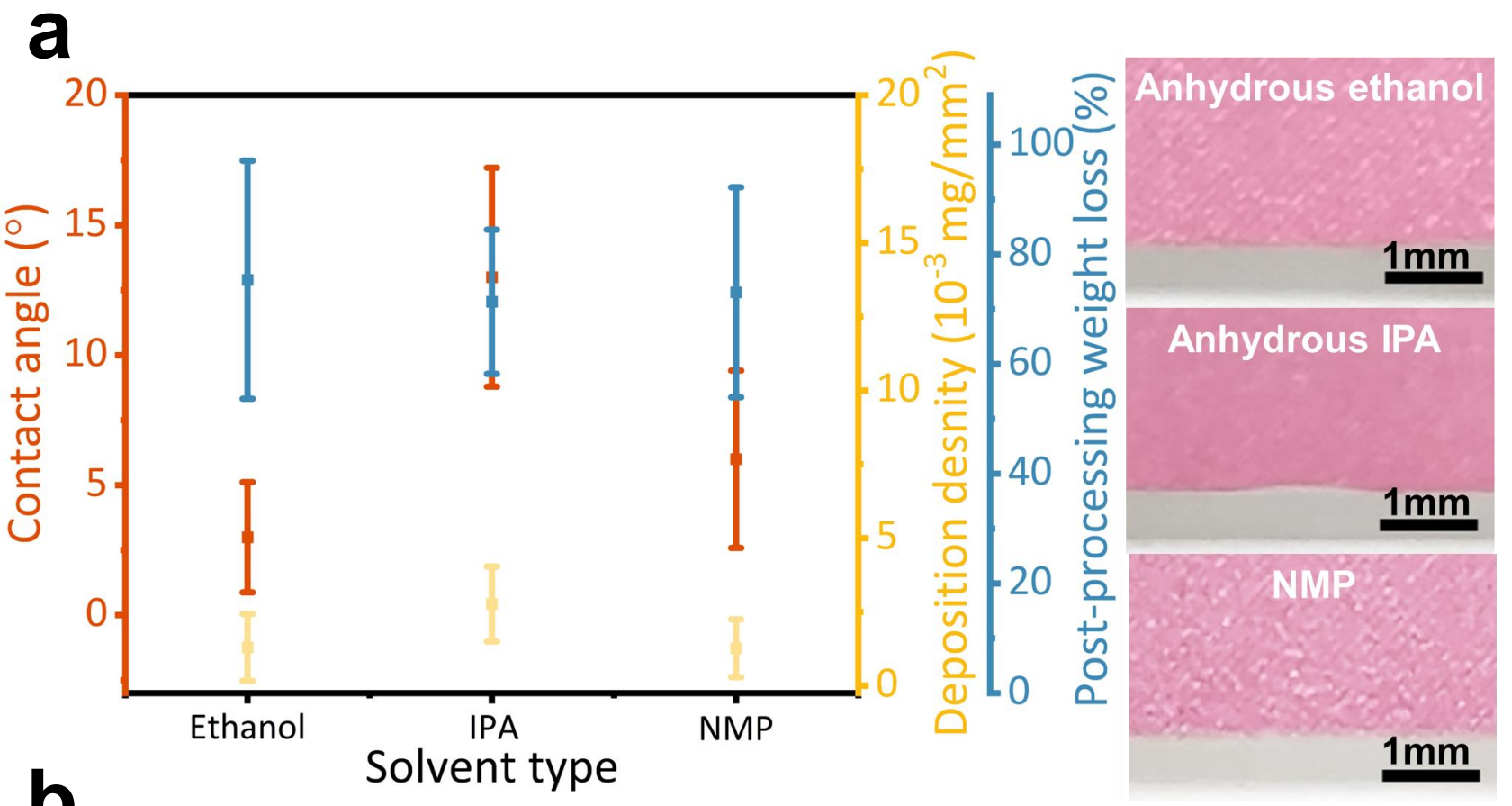

Nozzle diameter
Layer height
Ecoflex substrate mold
Neat EF
MWCNT@EF
c
Vapor finishing duration (s)
0
100
200
300
Printing line width / nozzle diamter
Infill line distance
Z-axis height (μm)
Horizontal measuring distance (μm)
d
Raw Ra=8.34±0.44μm
Over finishing
Resolution-limit Ra =2.14±0.17μm
Mild finishing
Moderate finishing
High finishing
Roughness average Ra (μm)
Vapor finishing duration (s)
e
Wavy
Flat
MWCNT@EF w/o PhS
Stress (MPa)
Strain (%)
f
MWCNT@EF w/ PhS
g
w/o PhS
G=131.9
W=155.8%
G=49.3
W=164.6%
G=22.4
W=240.4%
G=5.1
W=258.1%
ΔR/R0
h
w/ PhS
G=69.1
W=211.5%
G=27.0
W=230.4%
G=4.3
W=270.5%
G=4.1
W=271.7%

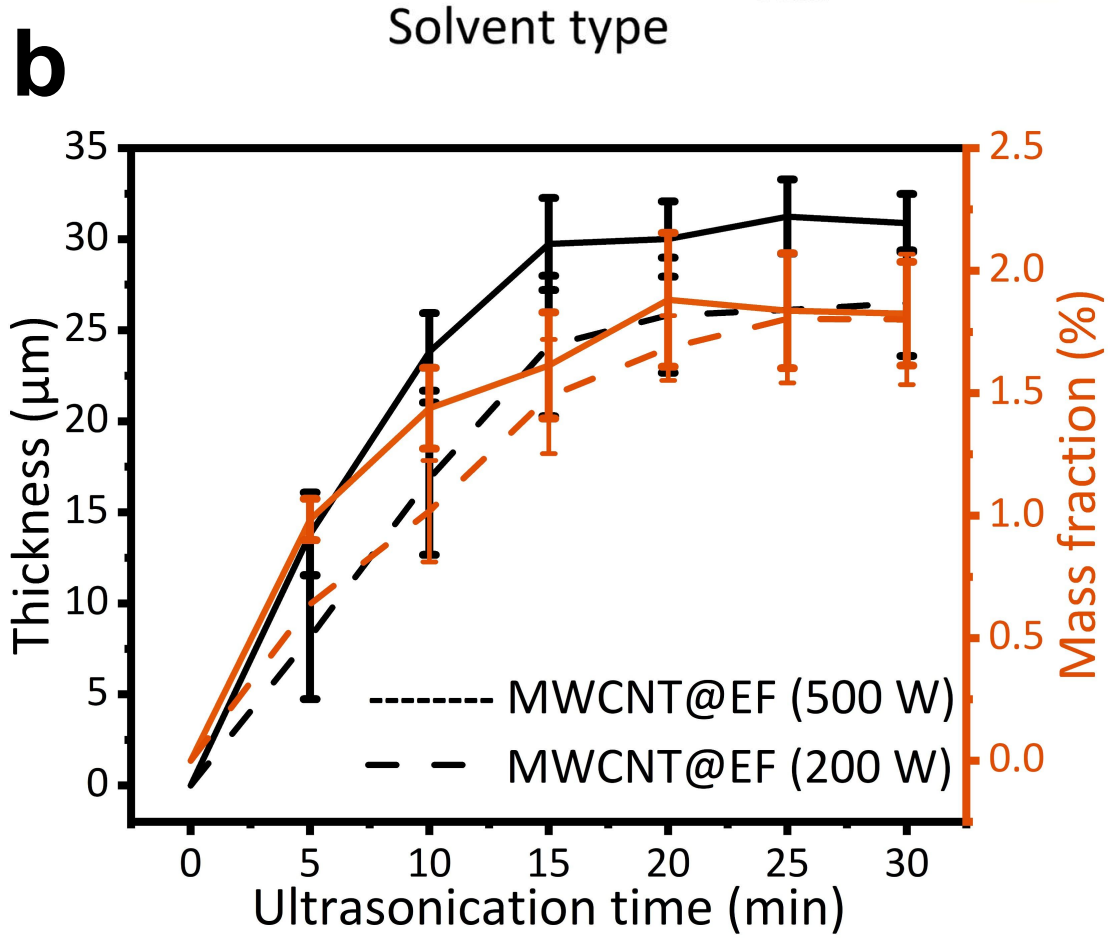

10 µm

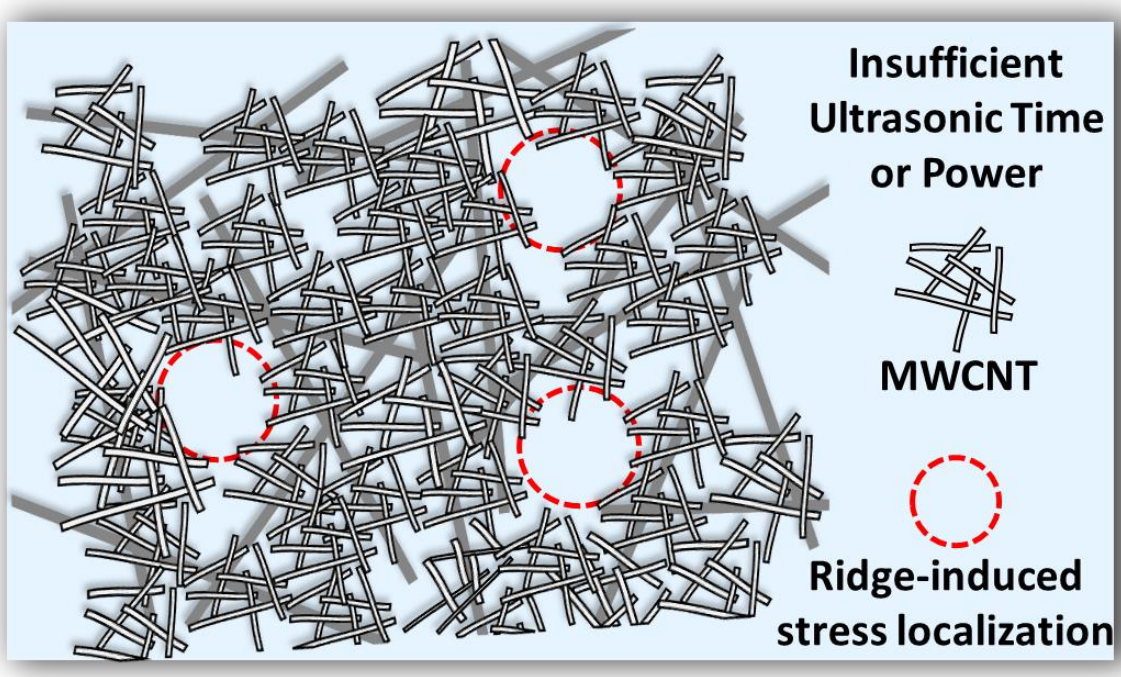

10 µm

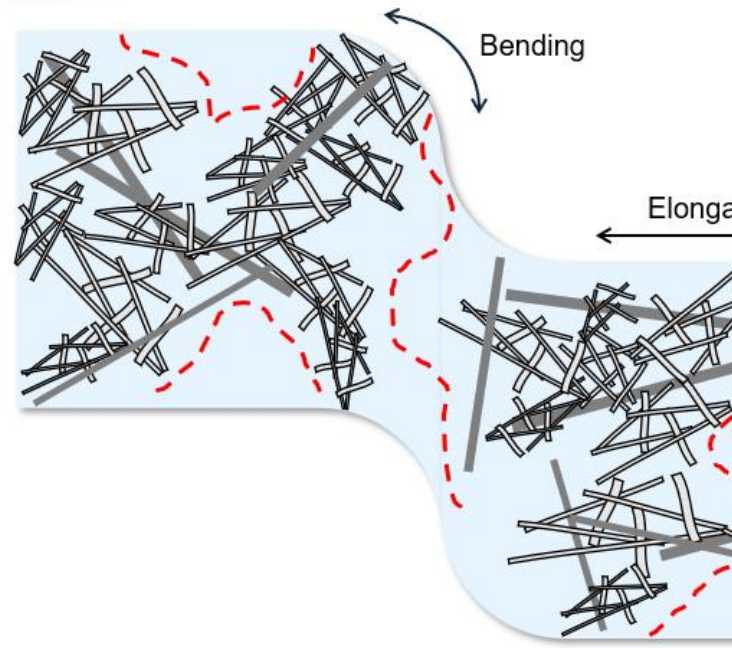


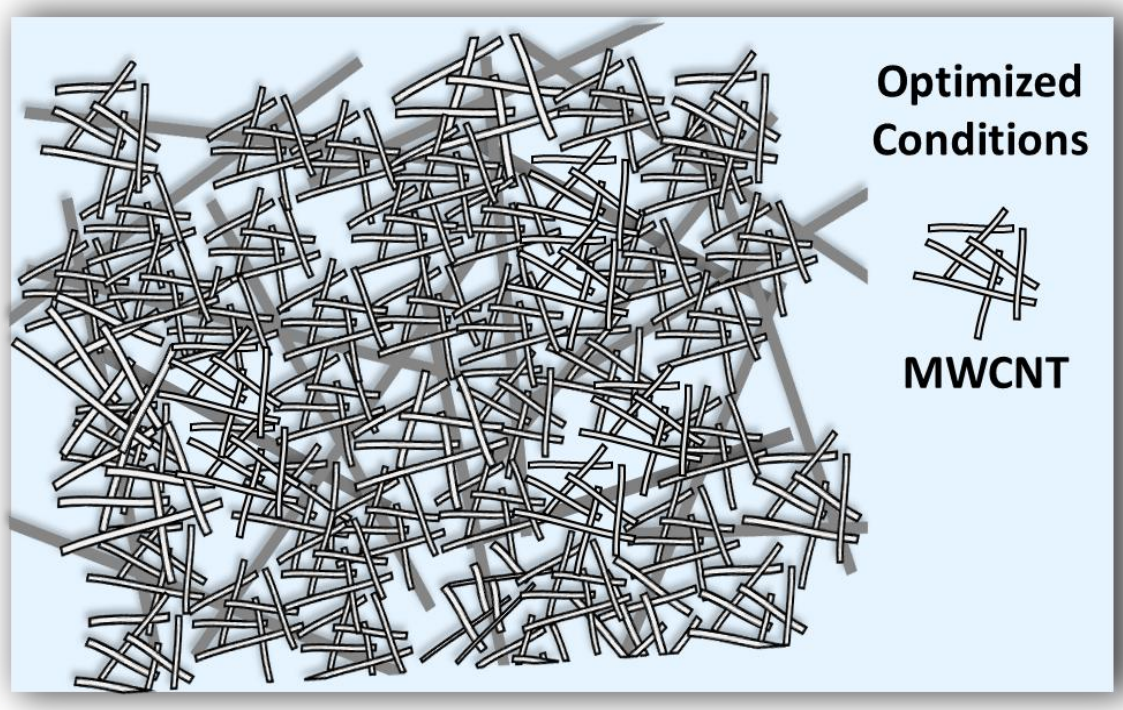

Experimental data
Boltzmann fit curve
Model fit curve
$$\rho_{deposition} = 21.45 \times \frac{1}{1 + \exp\left[\frac{(\eta - 30.13)}{12.91}\right]}$$
Deposition density (10^{-3} mg/mm^2)
25
20
15
10
5
0
0
50
100
Viscosity (mPa·s)

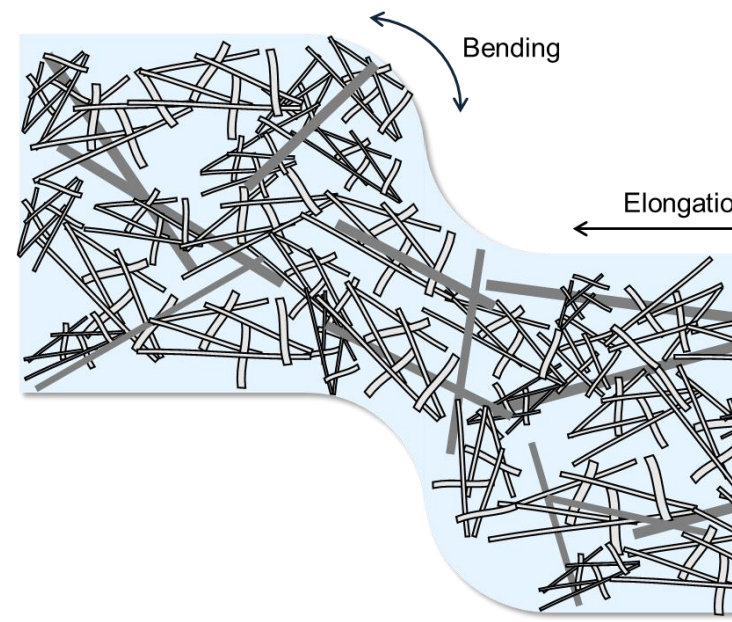

a
Contact angle (°)
Deposition desnity (10^{-3} mg/mm^2)
Post-processing weight loss (%)
Ethanol
IPA
NMP
Solvent type
Anhydrous ethanol
Anhydrous IPA
NMP
1mm
1mm
1mm

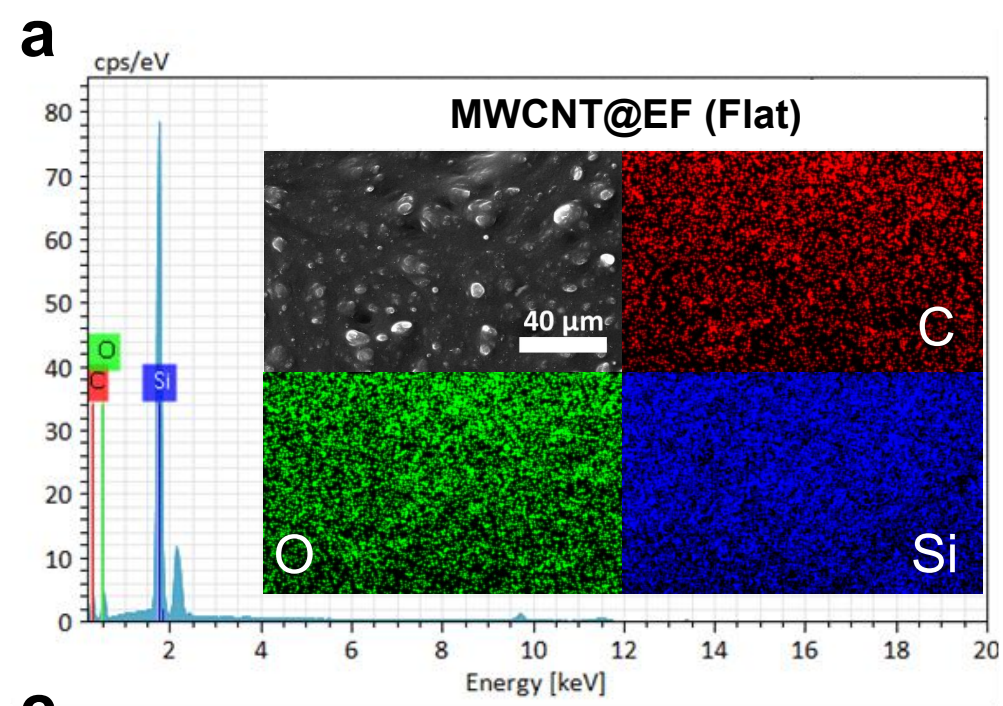

b
Thickness (μm)
Mass fraction (%)
Ultrasonication time (min)
MWCNT@EF (500 W)
MWCNT@EF (200 W)

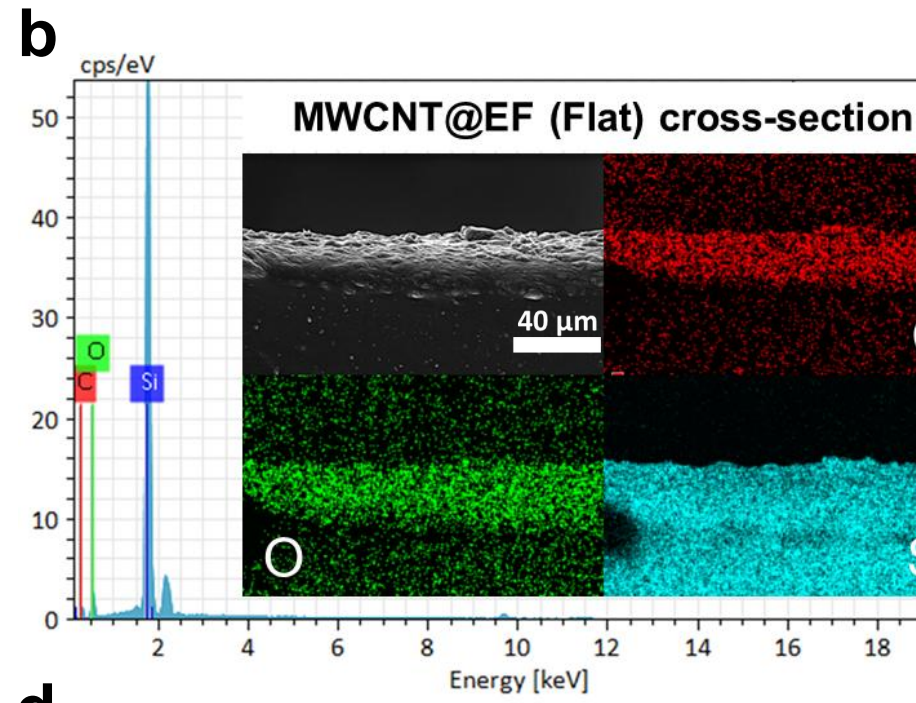

Insufficient
Ultrasonic Time
or Power
MWCNT
Ridge-induced
stress localization

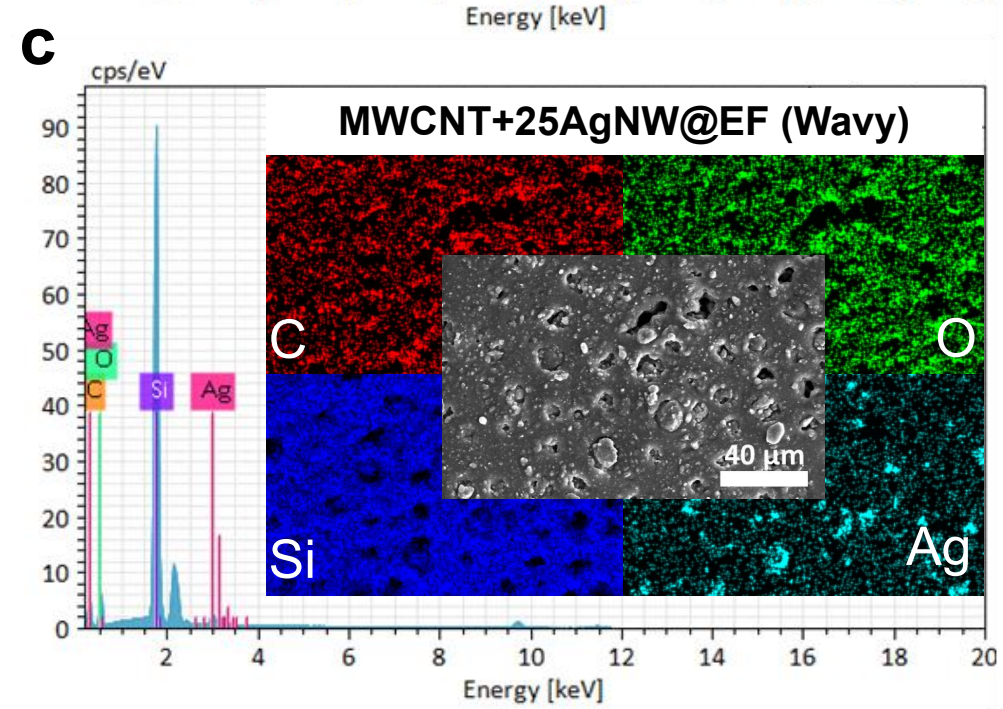

Bending
Elonga

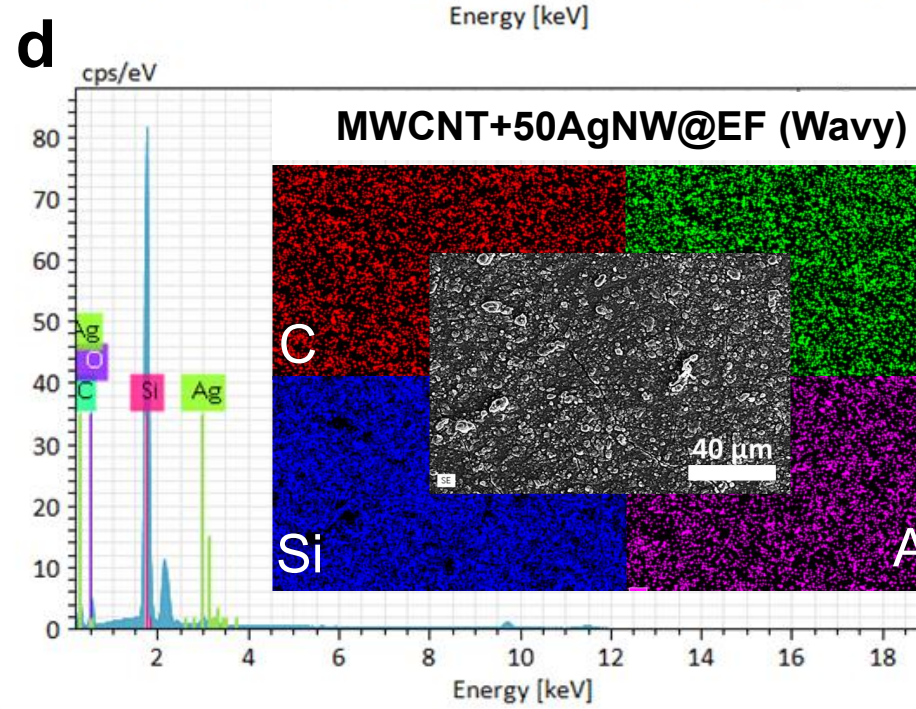

Optimized
Conditions
MWCNT

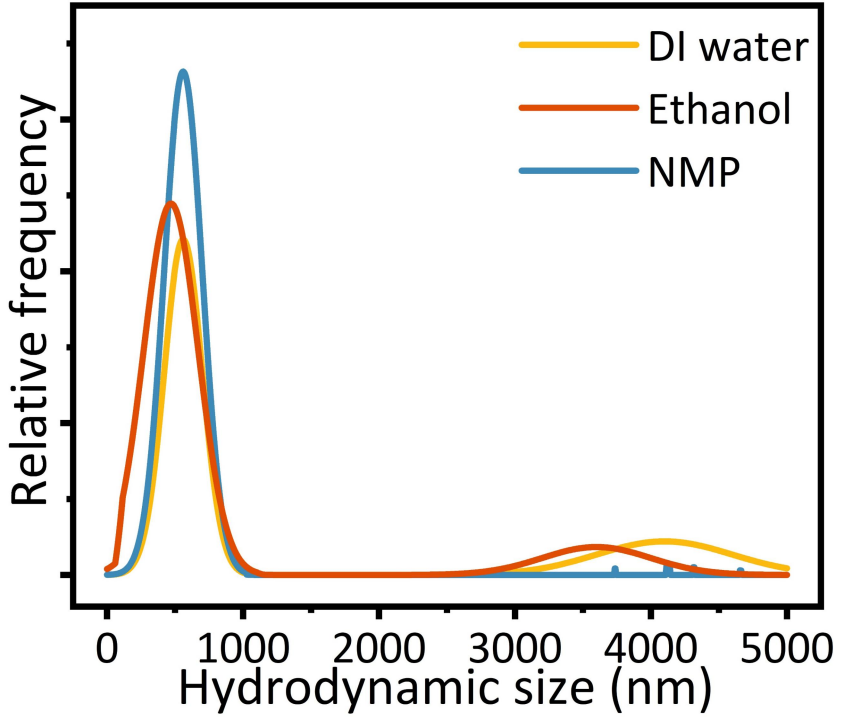

Bending
Elongatio

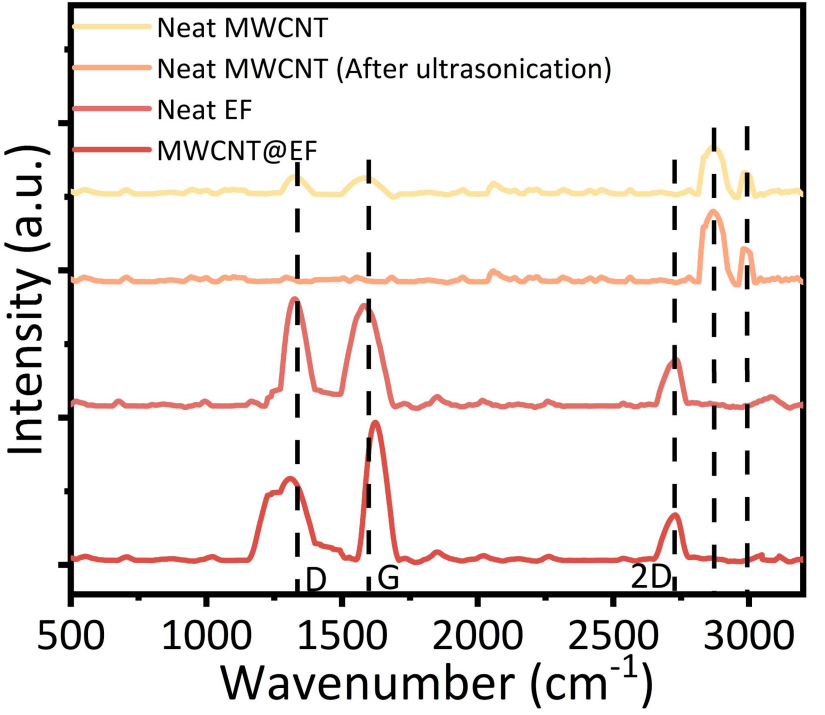

a
MWCNT@EF (Flat)
cps/eV
Energy [keV]
40 µm
C
O
Si

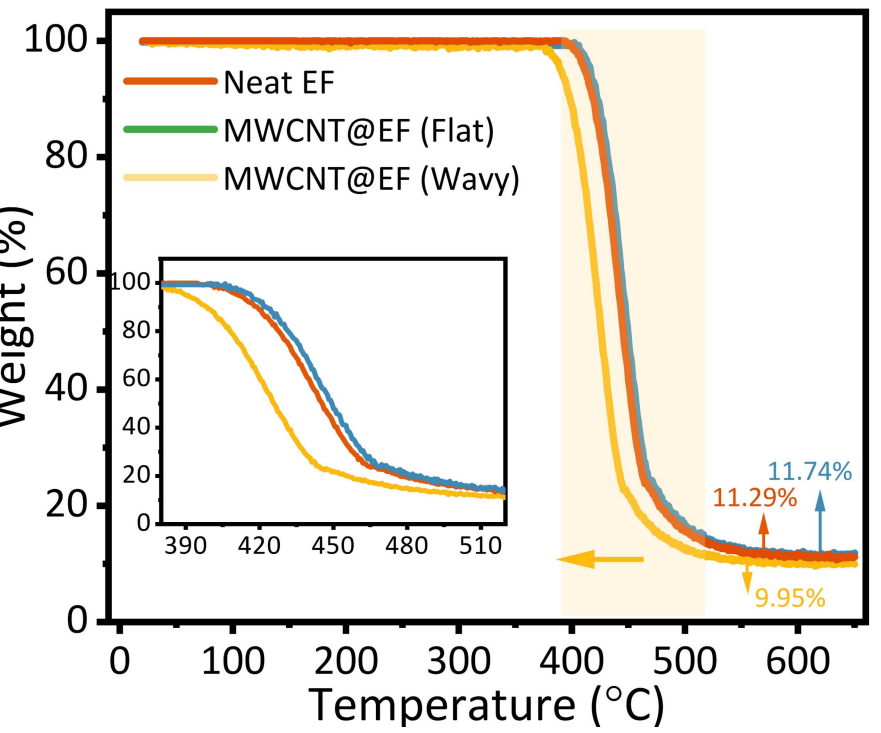

b
MWCNT@EF (Flat) cross-section
cps/eV
Energy [keV]
40 µm
O

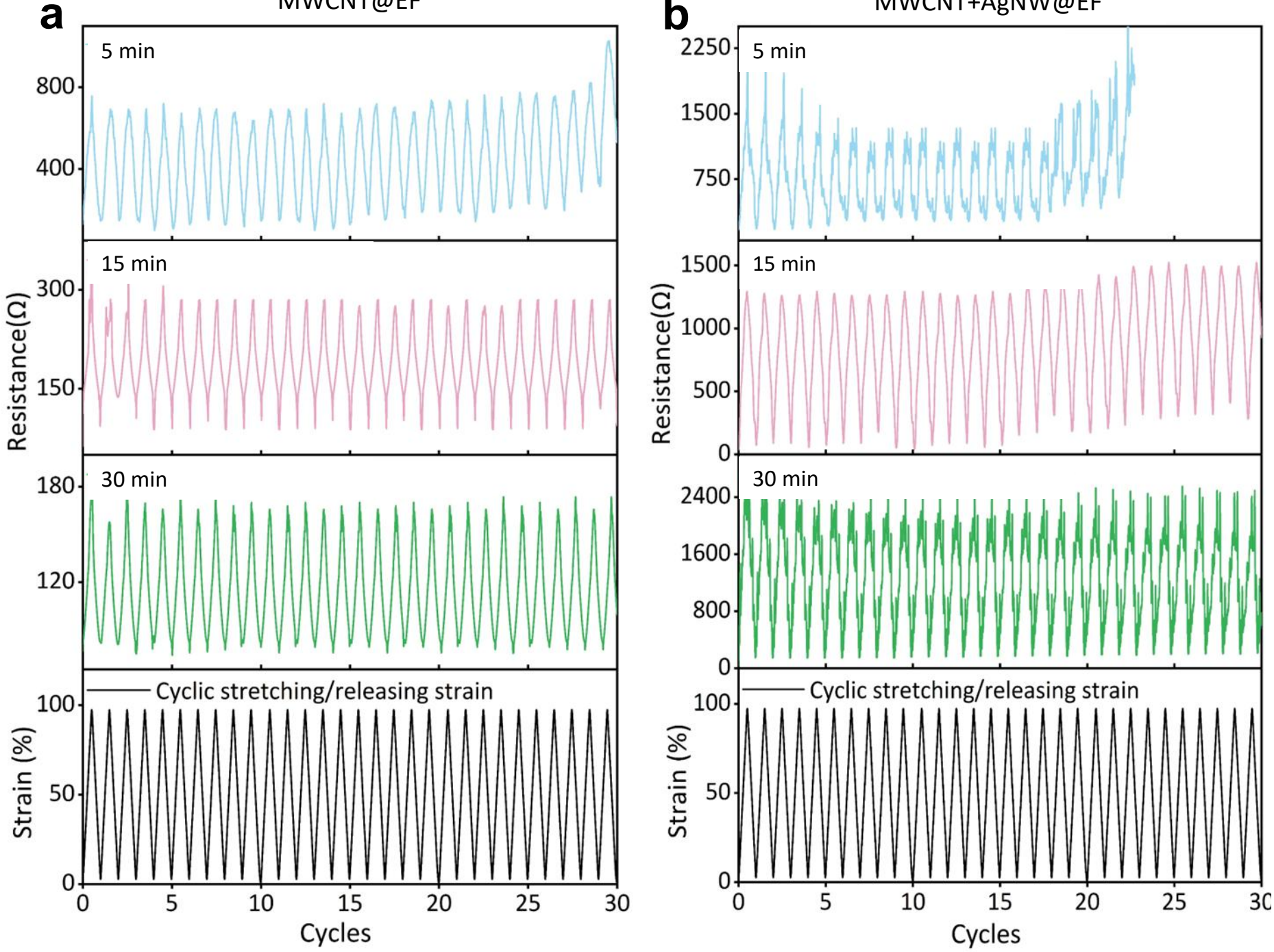

c
MWCNT+25AgNW@EF (Wavy)
cps/eV
Energy [keV]
40 µm
C
O
Si
Ag


d
MWCNT+50AgNW@EF (Wavy)
cps/eV
Energy [keV]
40 µm
C
Si

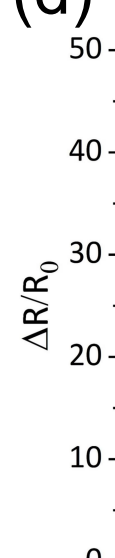

DI water
Ethanol
NMP
Relative frequency
0
1000
2000
3000
4000
5000
Hydrodynamic size (nm)

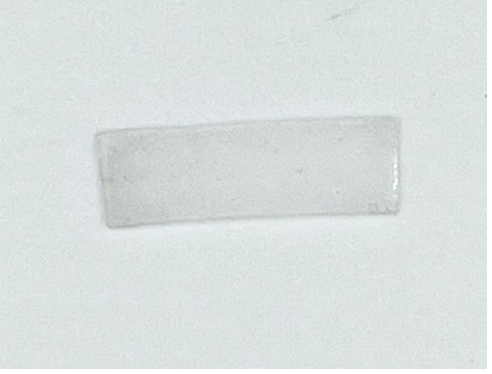
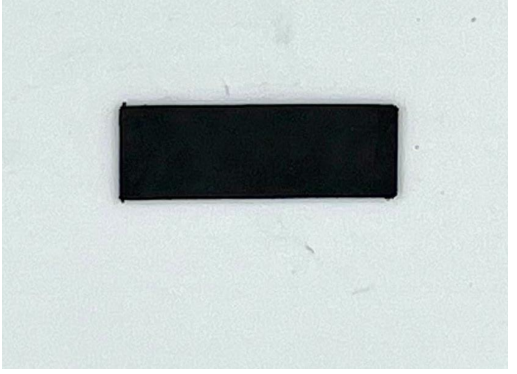

Neat MWCNT
Neat MWCNT (After ultrasonication)
Neat EF
MWCNT@EF
Intensity (a.u.)
D
G
2D
500
1000
1500
2000
2500
3000
Wavenumber (cm-1)

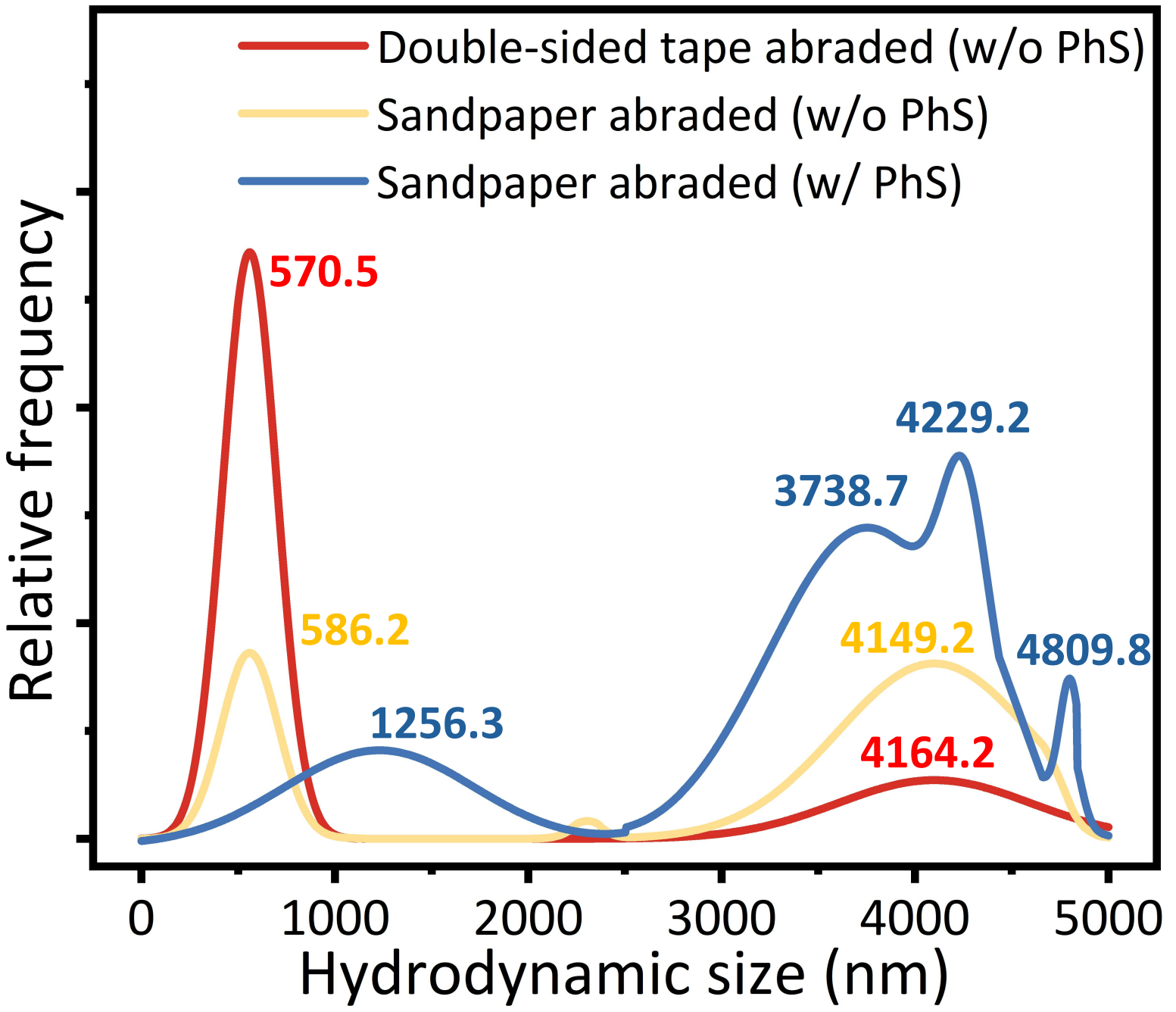

Neat EF
MWCNT@EF (Flat)
MWCNT@EF (Wavy)
Weight (%)
100
80
60
40
20
0
390
420
450
480
510
11.74%
11.29%
9.95%
0
100
200
300
400
500
600
Temperature (°C)

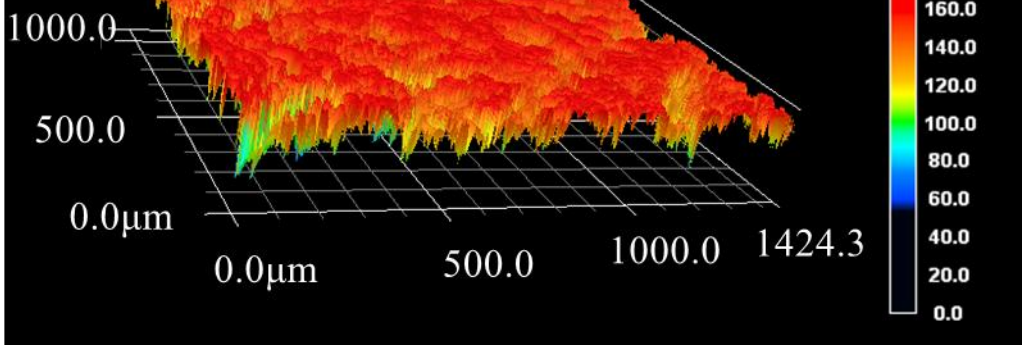

a
MWCNT@EF
b
MWCNT+AgNW@EF
5 min
15 min
30 min
Resistance(Ω)
Cyclic stretching/releasing strain
Strain (%)
Cycles

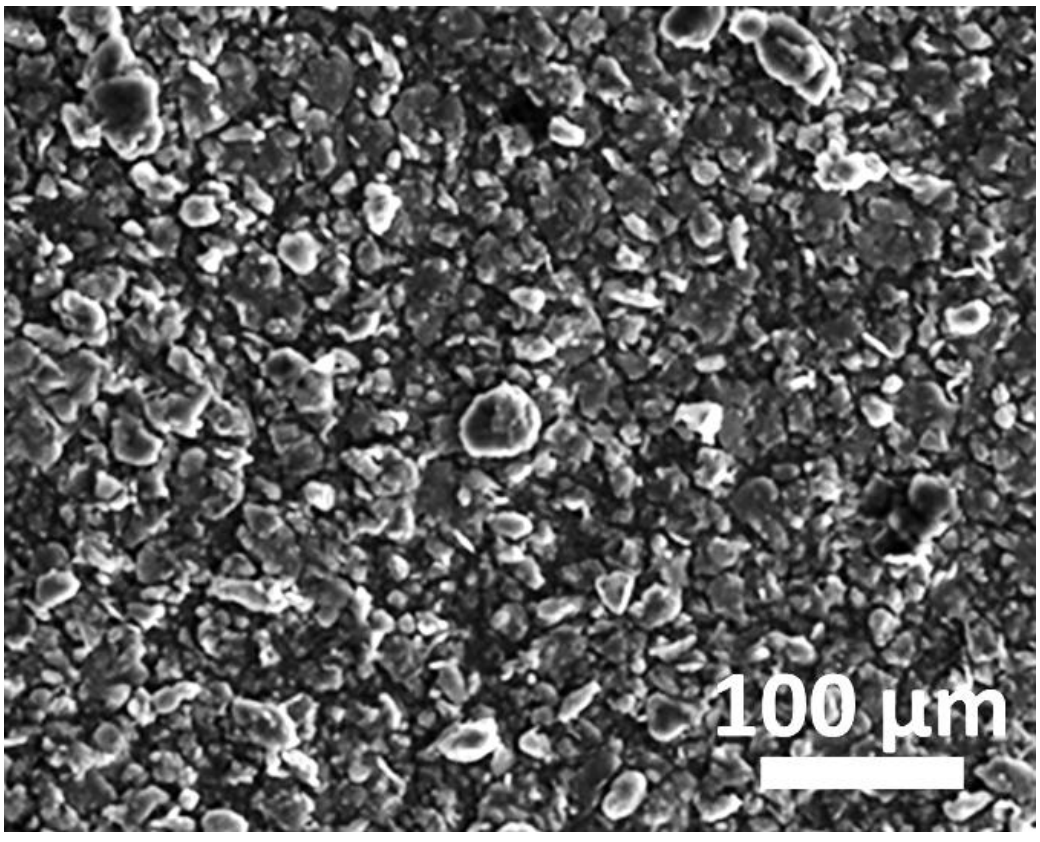
(d)

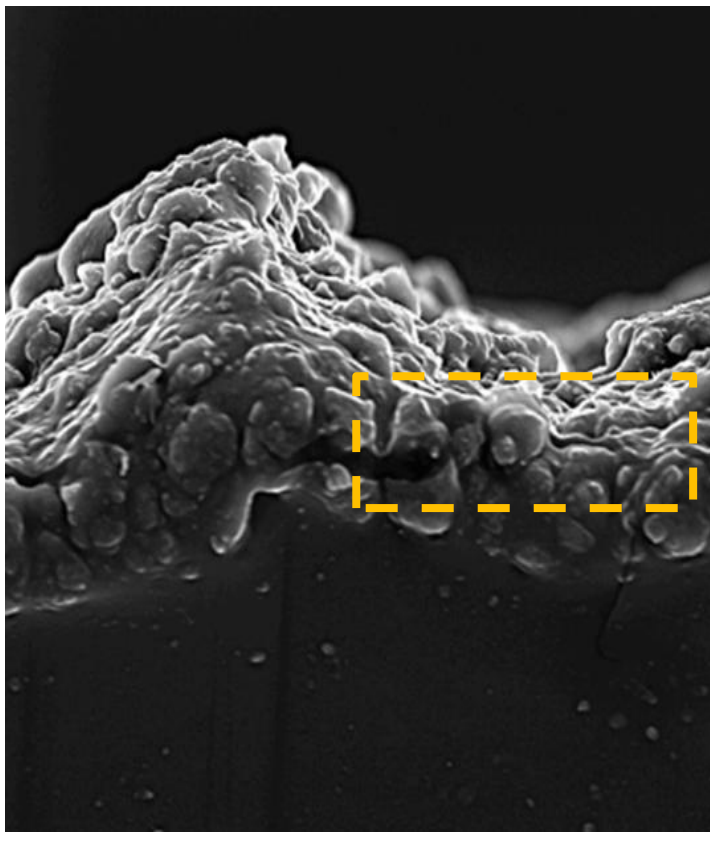

ΔR/R0

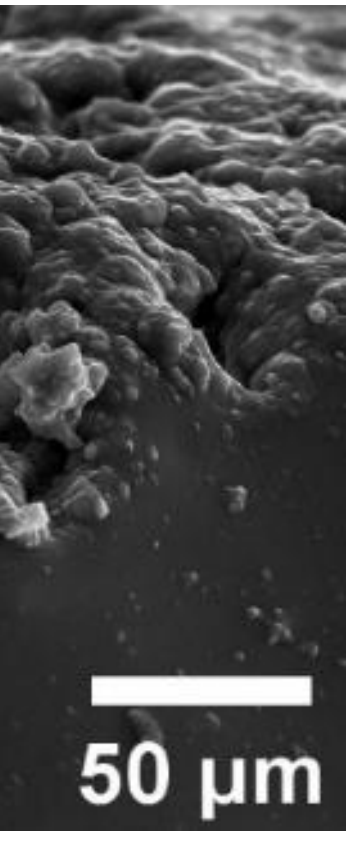



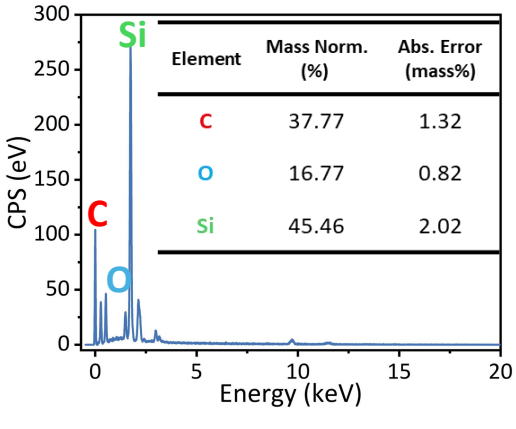

Double-sided tape abraded (w/o PhS)
Sandpaper abraded (w/o PhS)
Sandpaper abraded (w/ PhS)
570.5
586.2
1256.3
3738.7
4229.2
4149.2
4809.8
4164.2
Relative frequency
0
1000
2000
3000
4000
5000
Hydrodynamic size (nm)



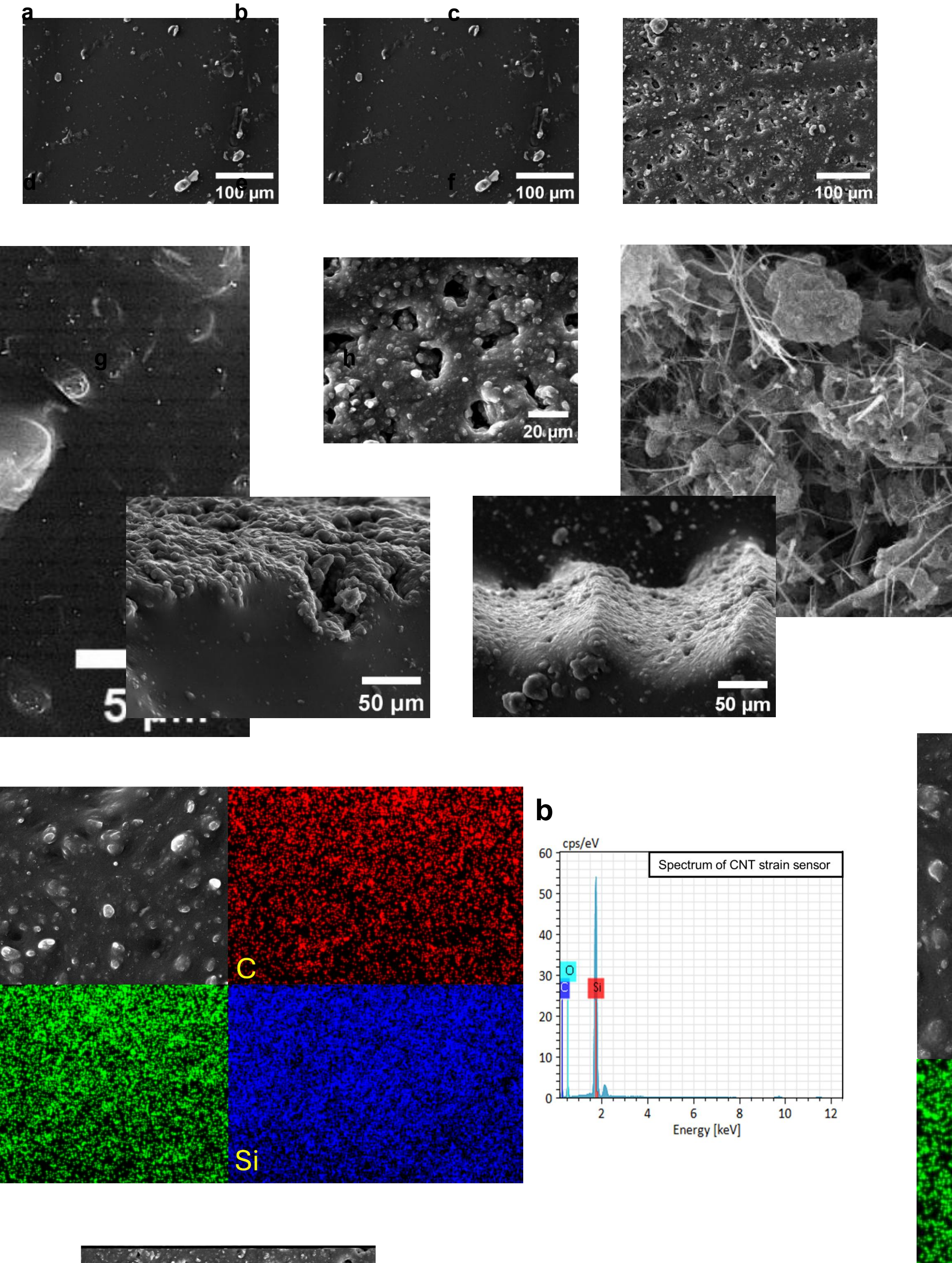


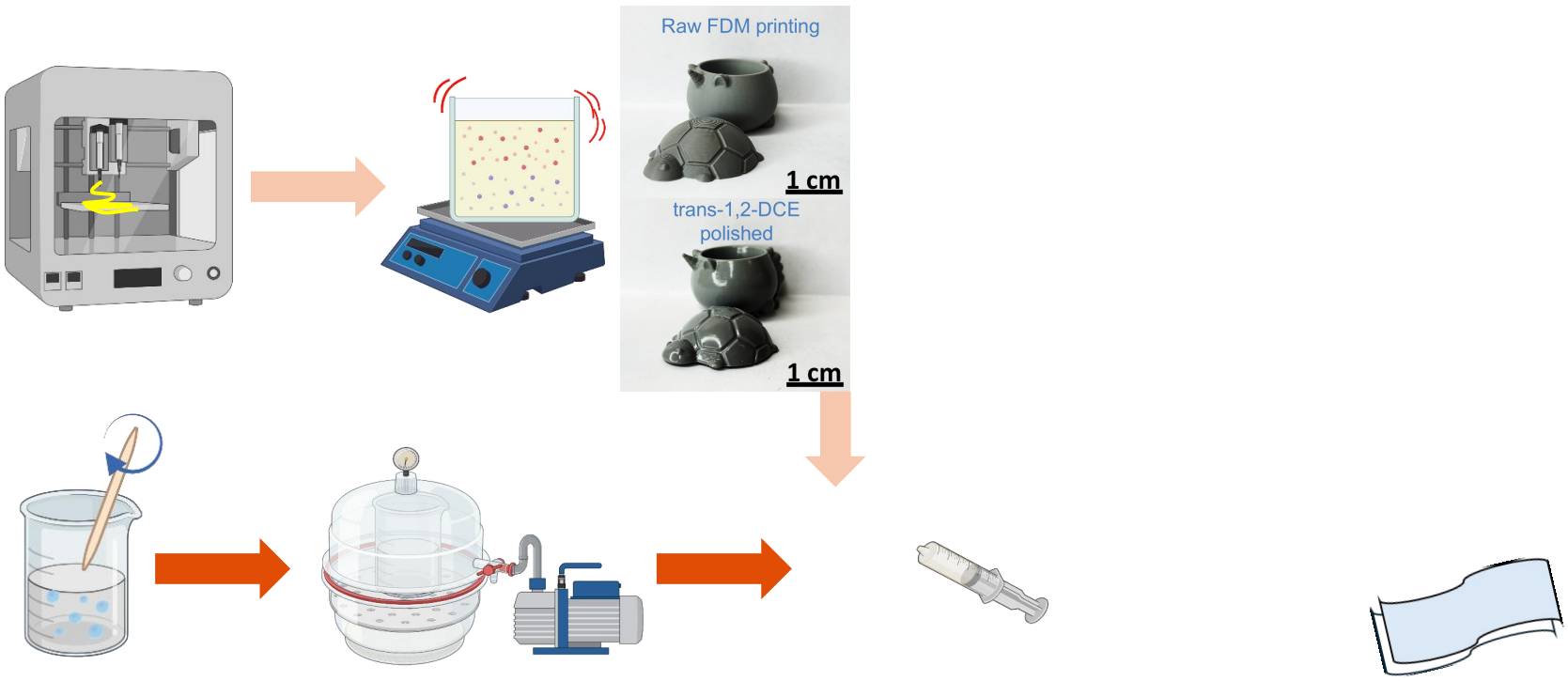


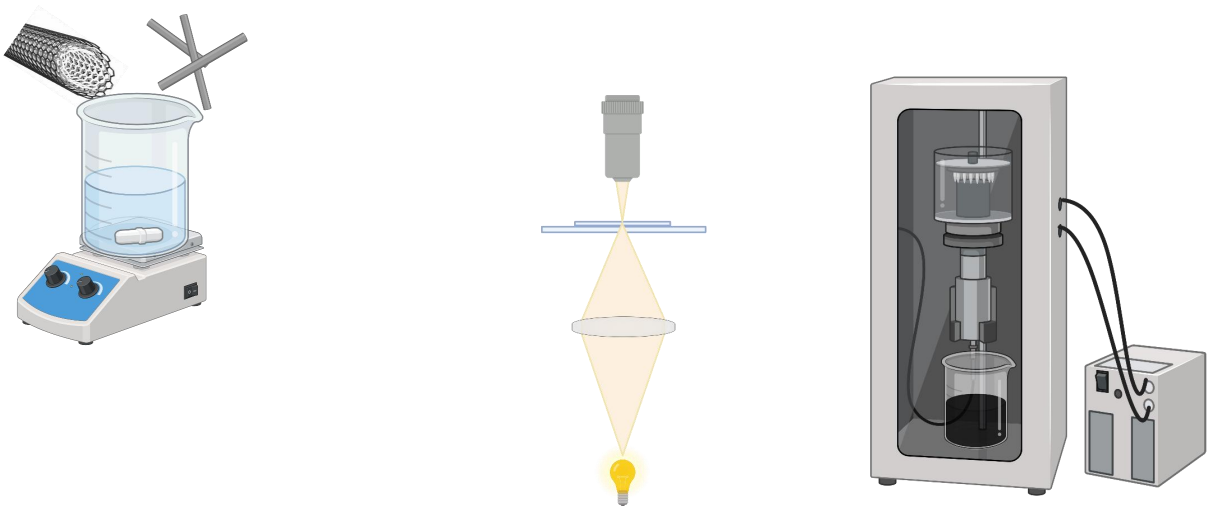


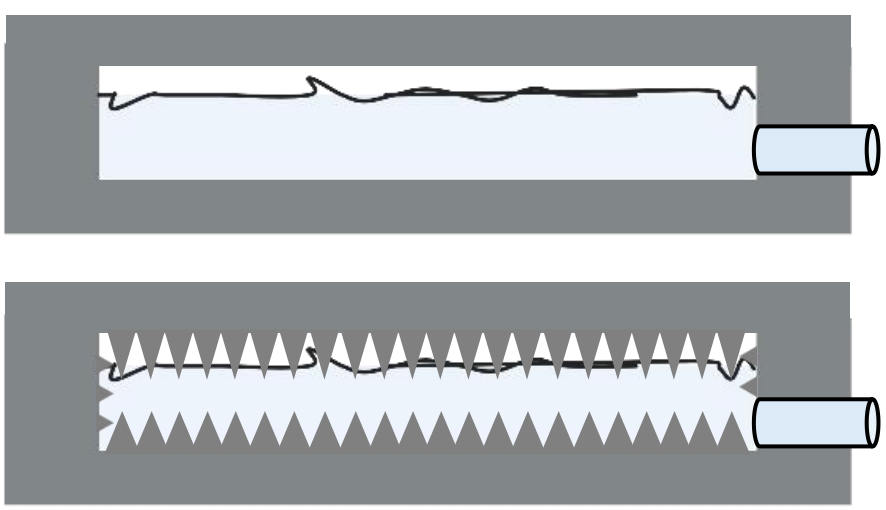


Element	Mass Norm. (%)	Abs. Error (mass%)
C	37.77	1.32
O	16.77	0.82
Si	45.46	2.02

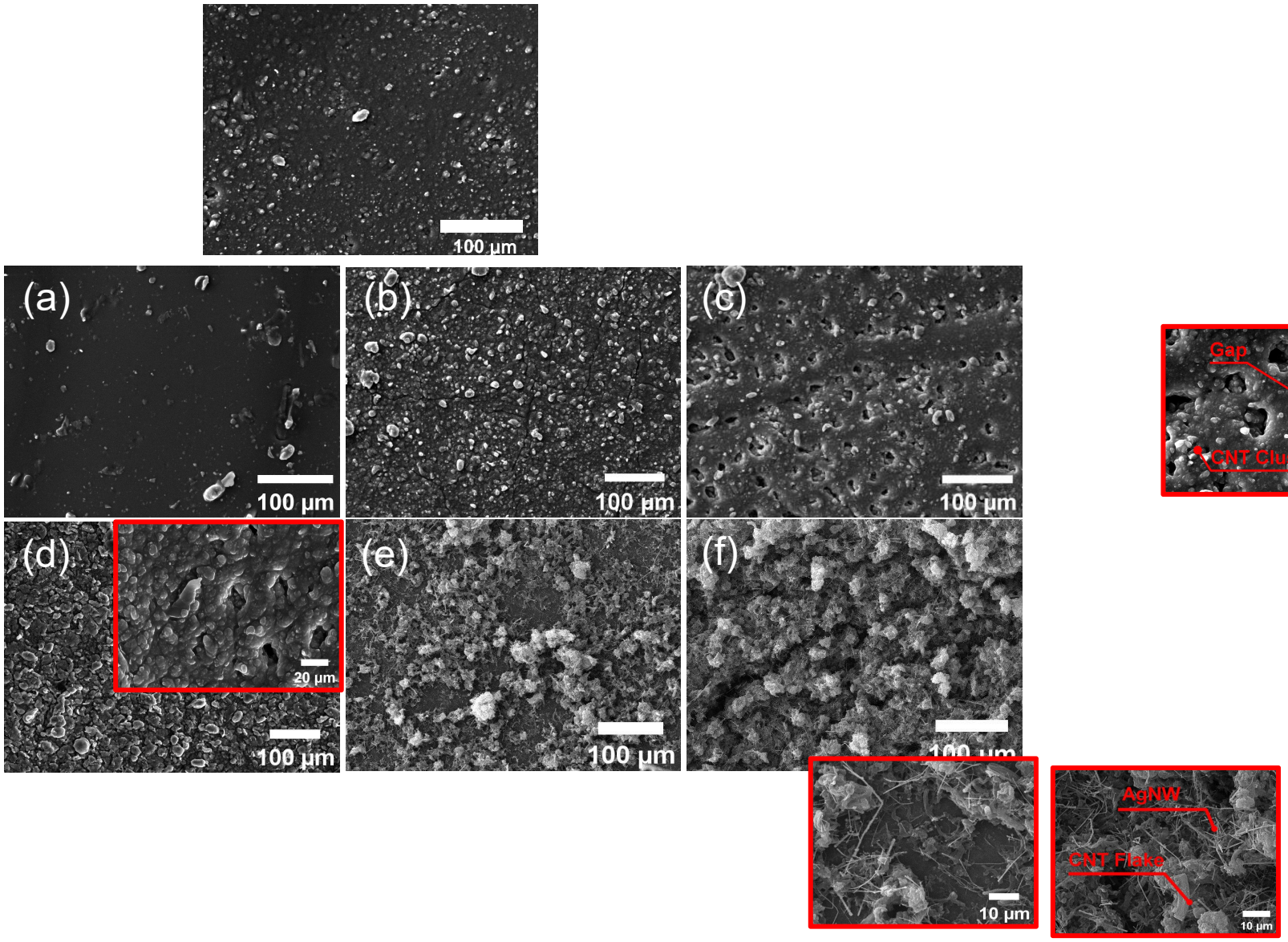

a
b
c
d
e
100 µm
f
100 µm
100 µm
g
h
20 µm
5
50 µm
50 µm
C
Si
b
cps/eV
Spectrum of CNT strain sensor
O
C
Si
Energy [keV]


Raw FDM printing
1 cm
trans-1,2-DCE
polished
1 cm



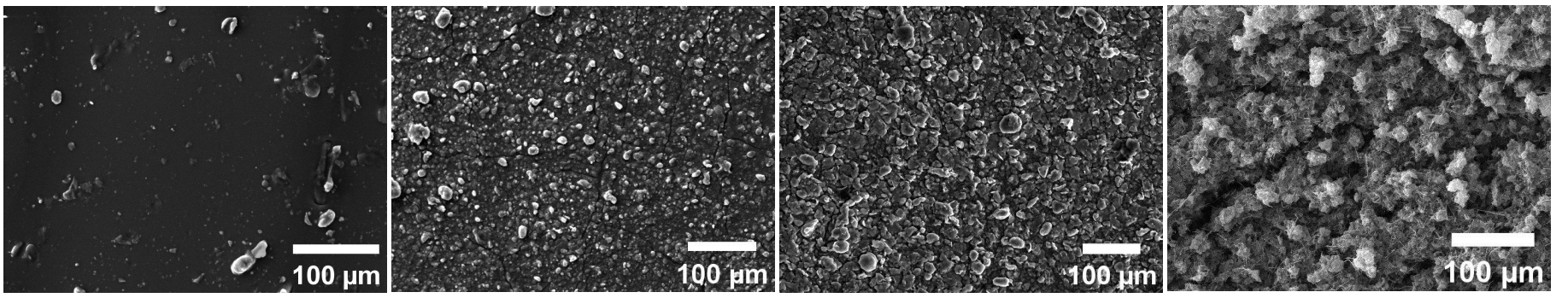


Raw FDM

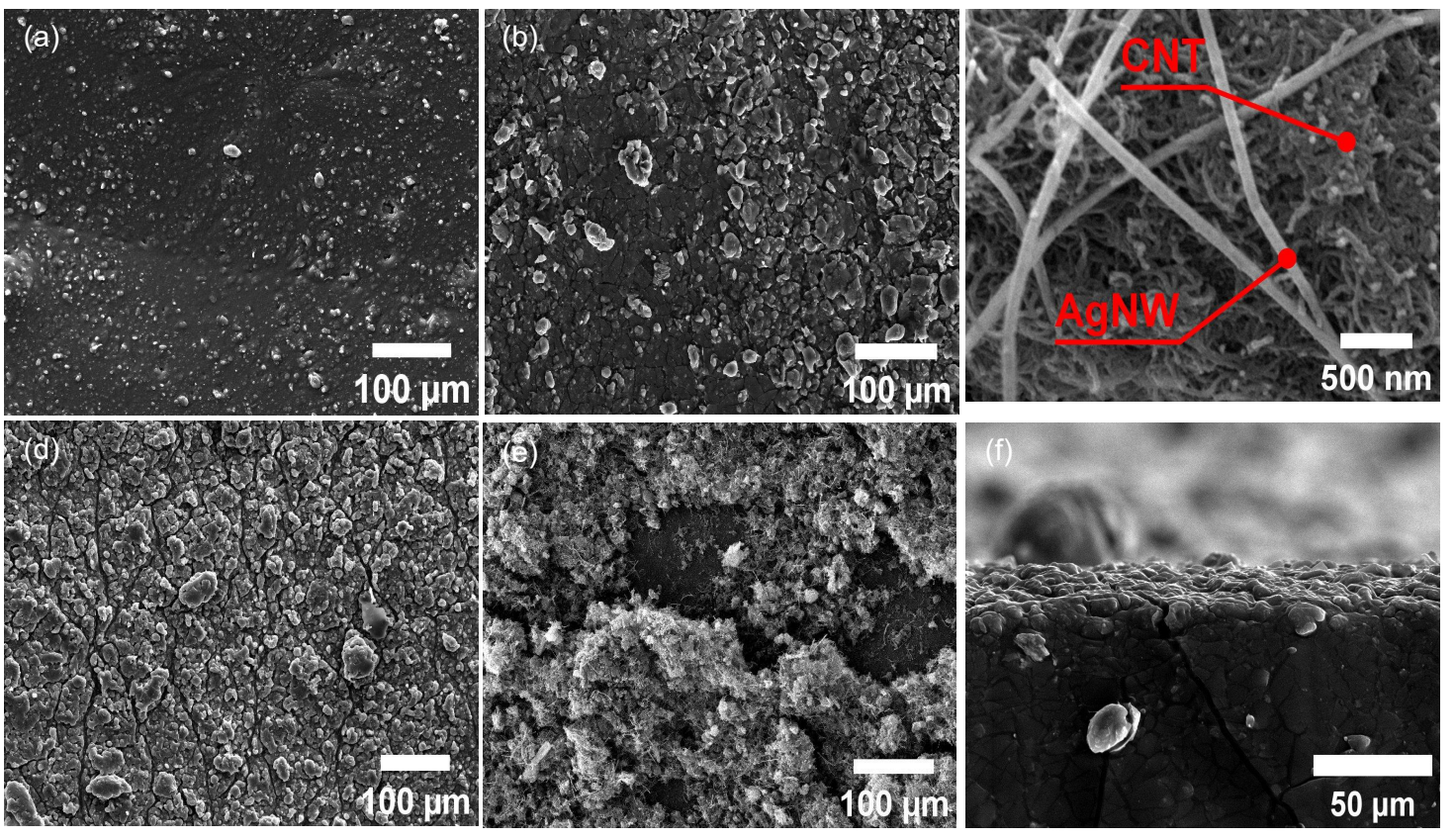

100 µm
(a)
100 µm
(b)
100 µm
(c)
100 µm
Gap
CNT Cluster
(d)
20 µm
100 µm
(e)
100 µm
(f)
100 µm
10 µm
AgNW
CNT Flake
10 µm

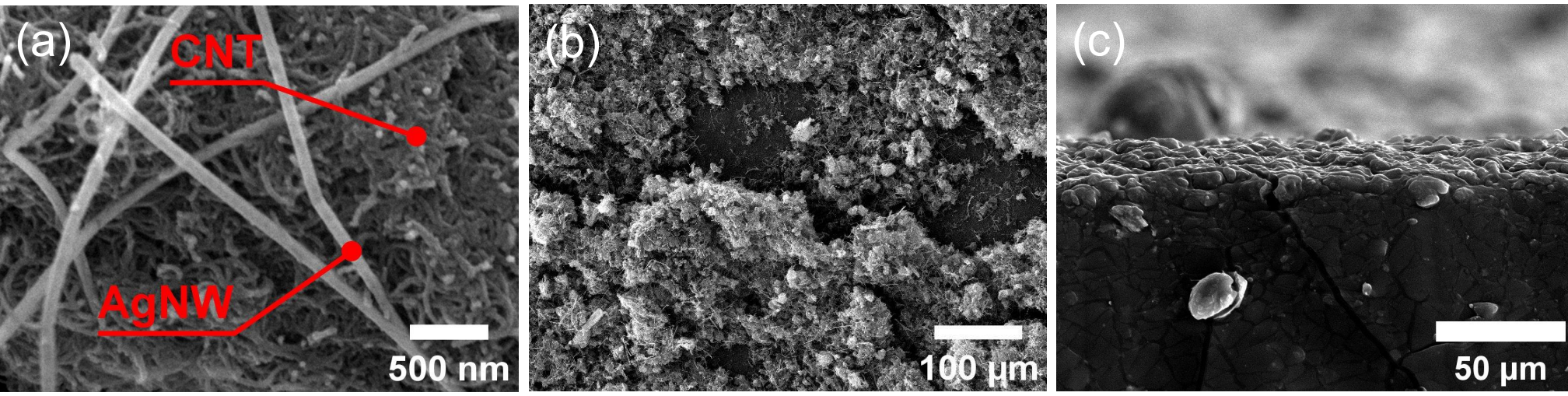
Key Findings

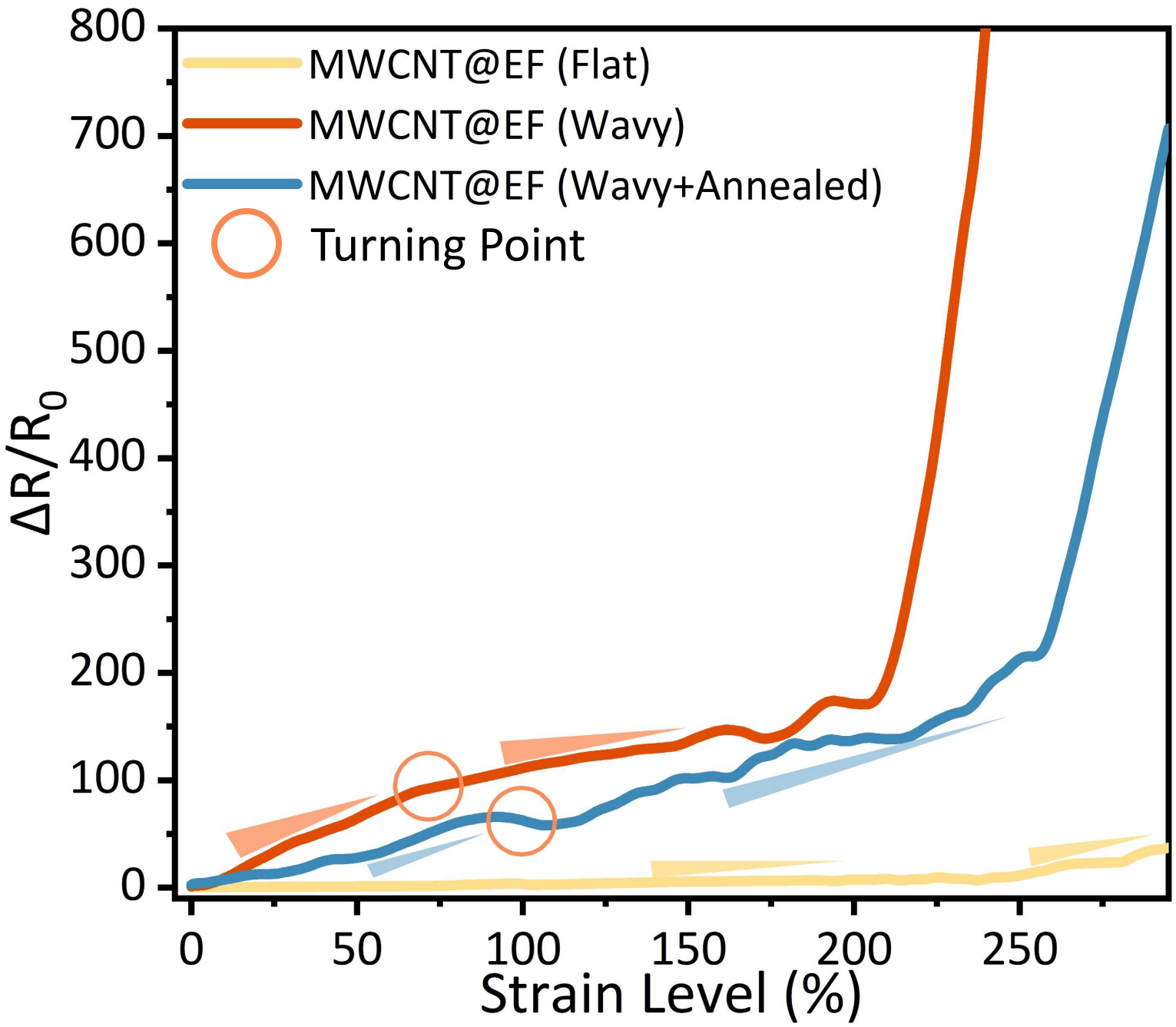
1. It is feasible to ultrasonically assemble hybrid materials onto the Ecoflex surface



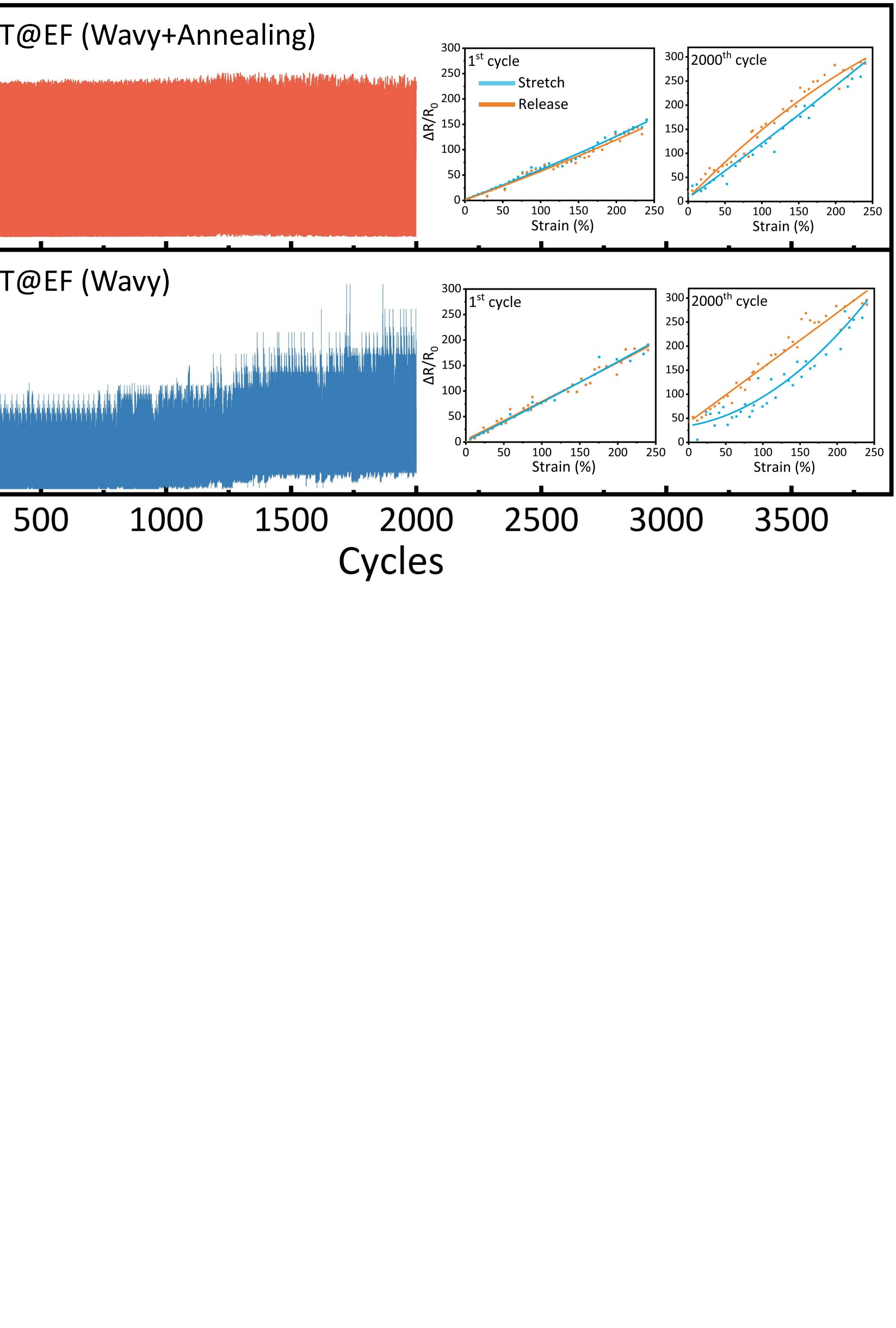
Ecoflex | Ecoflex +CNT | Ecoflex+CNT/AgNW (low power level) | Ecoflex+CNT/AgNW (high power level)

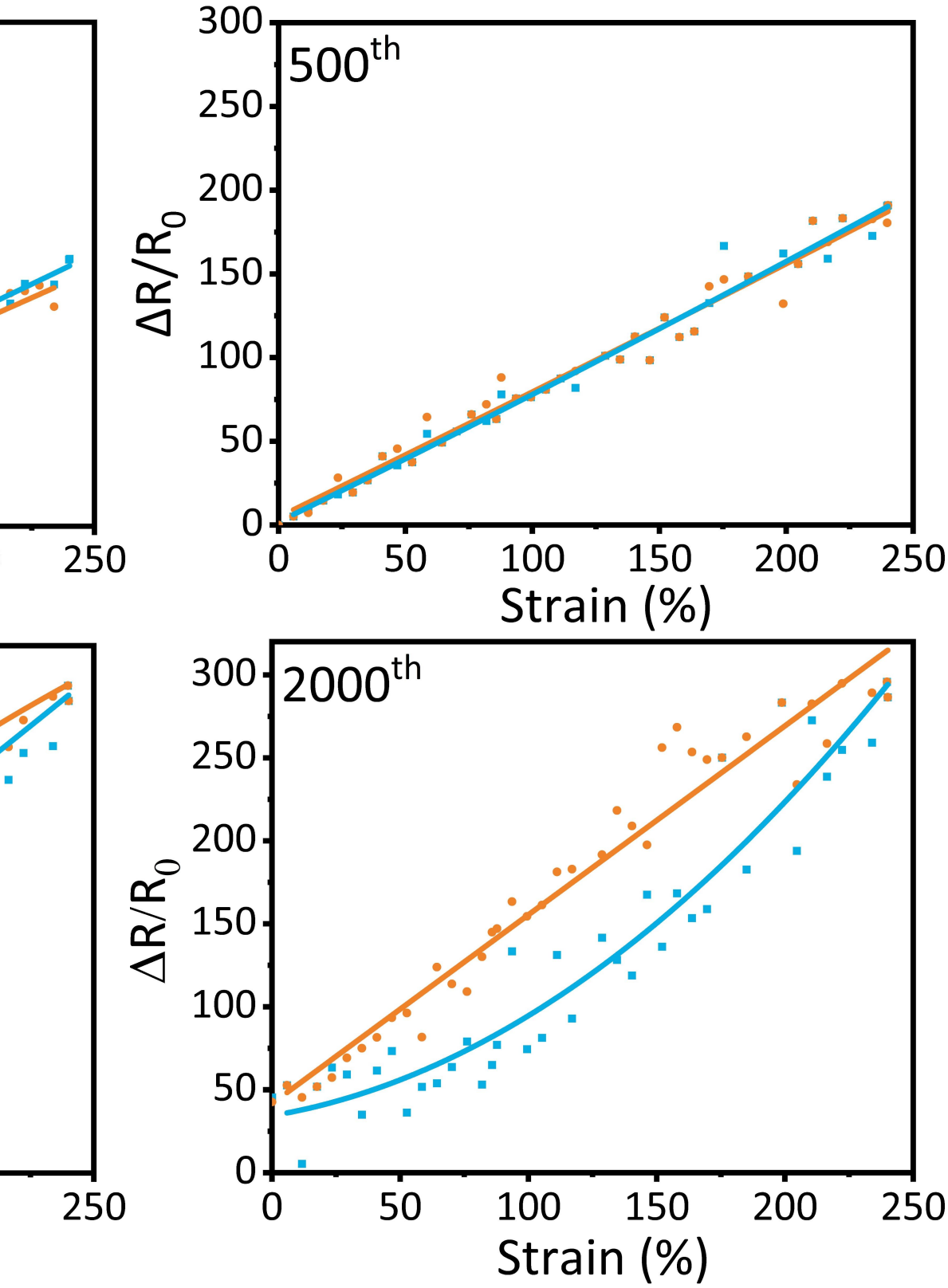

(a)
100 μm
(b)
100 μm
CNT
AgNW
500 nm
(d)
100 μm
(e)
100 μm
(f)
50 μm

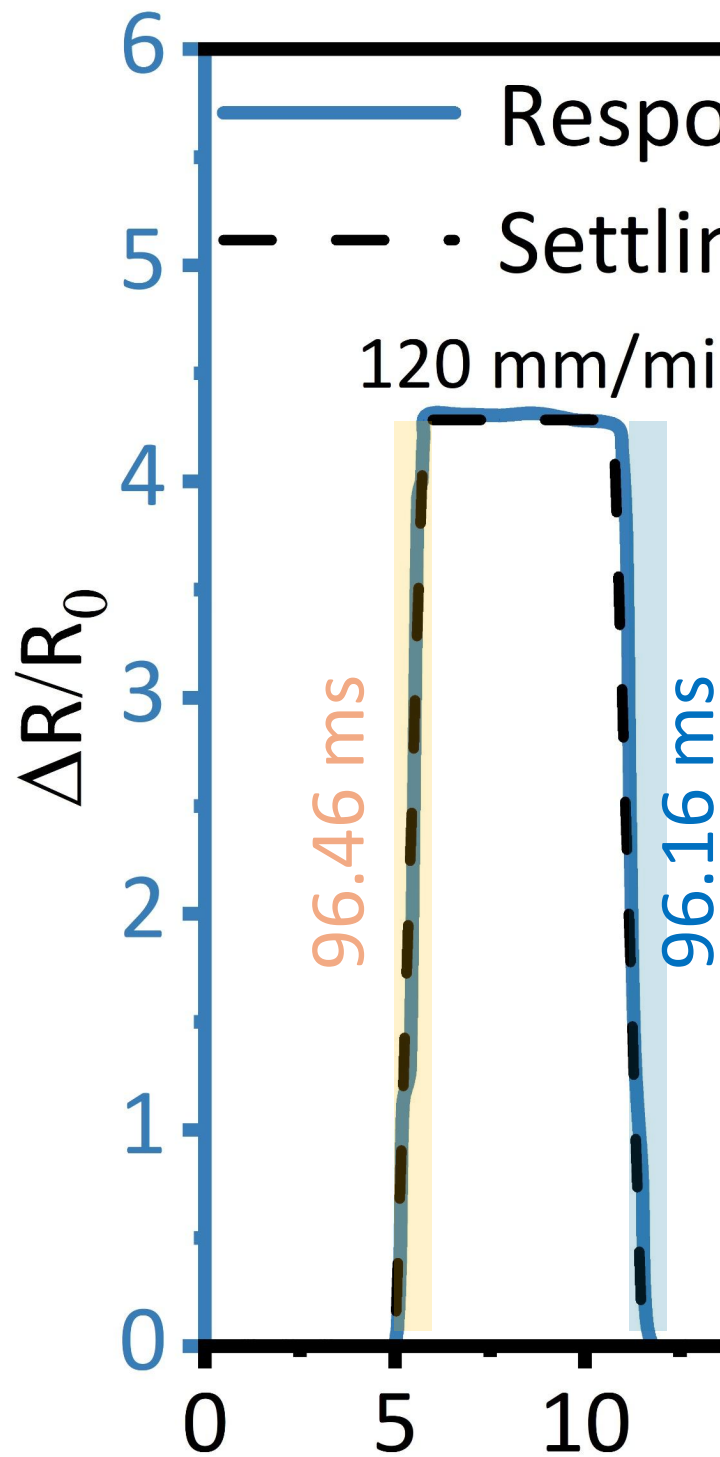

(a)
CNT
AgNW
500 nm
(b)
100 μm
(c)
50 μm

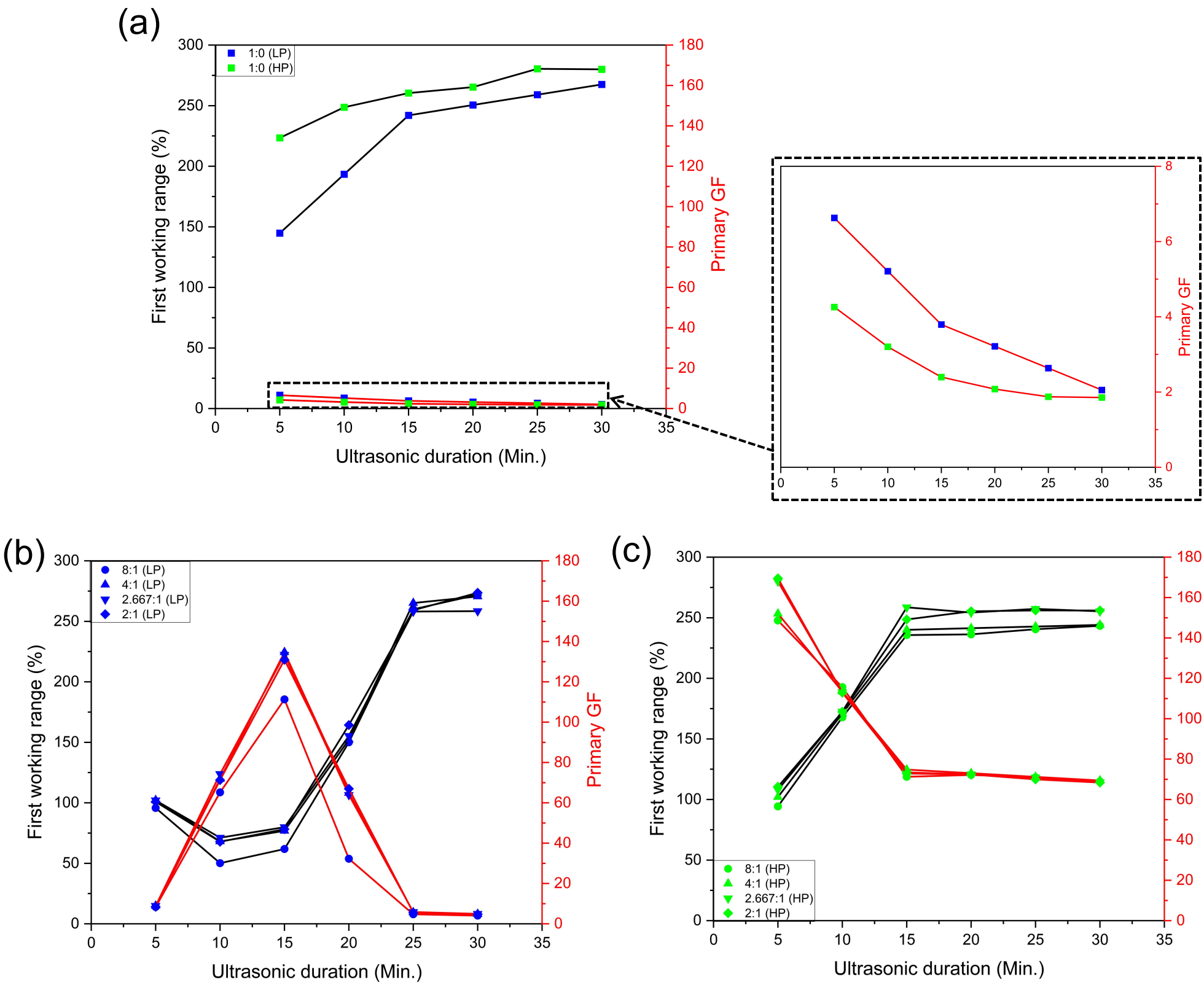


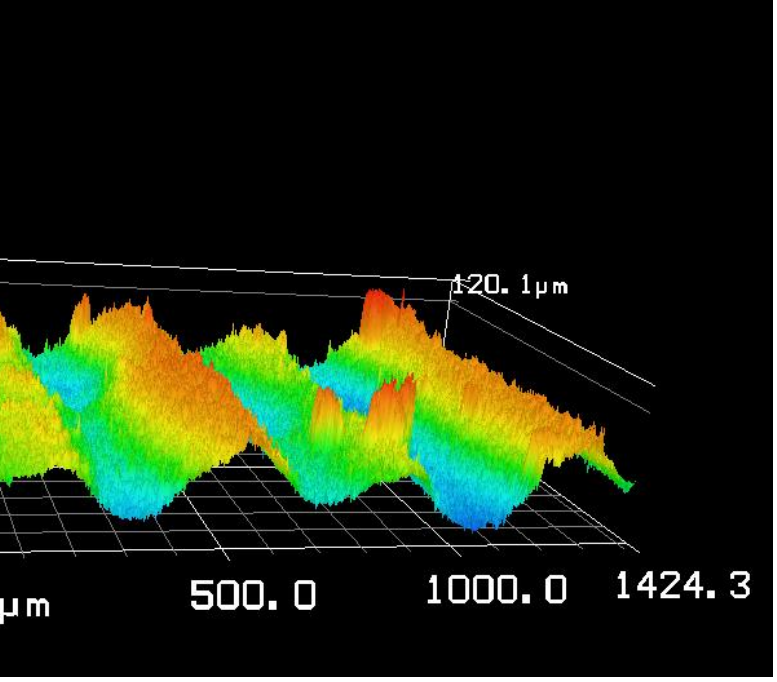
G
3.8 (R²=0
135 (R²=0
73. (R²=0

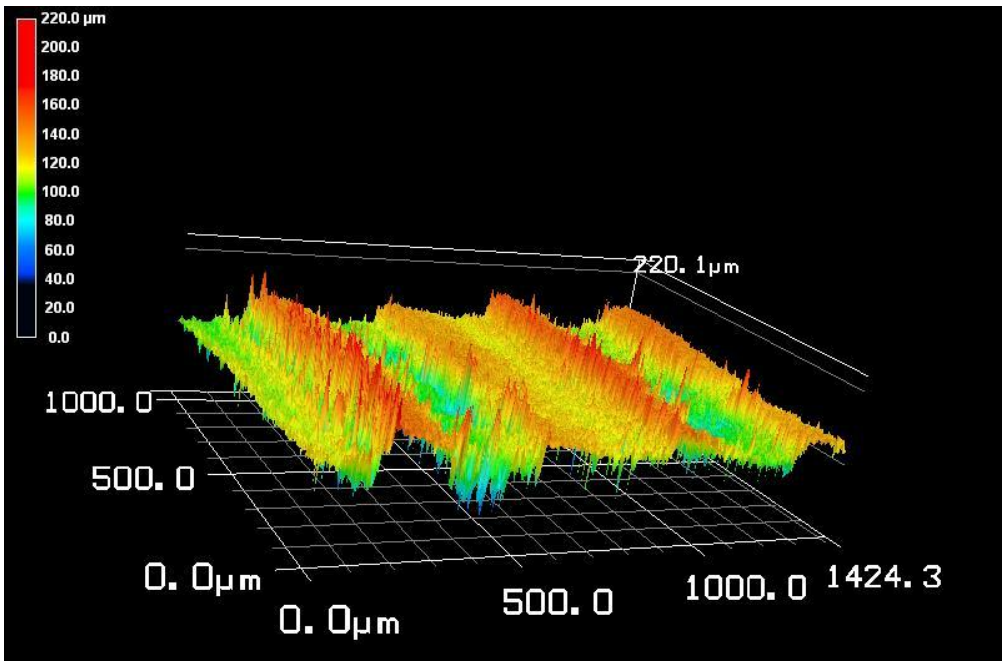

T@EF (Wavy+Annealing)
1st cycle
Stretch
Release
2000th cycle
ΔR/R0
Strain (%)
T@EF (Wavy)
1st cycle
2000th cycle
ΔR/R0
Strain (%)
500
1000
1500
2000
2500
3000
3500
Cycles


500th
2000th
ΔR/R0
Strain (%)
0
50
100
150
200
250
300

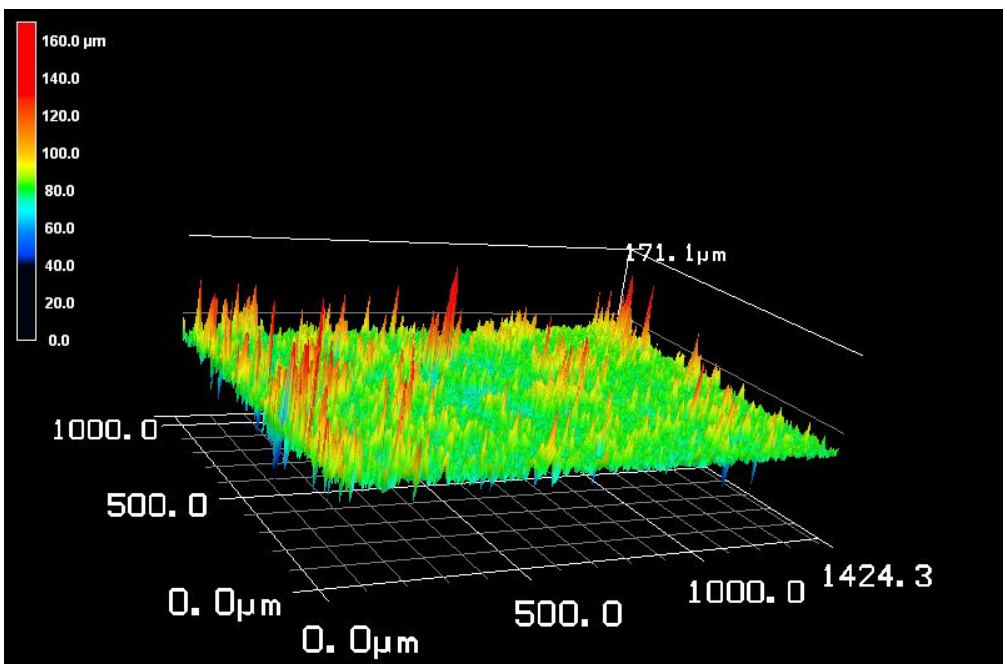

Respo
Settlin
120 mm/mi
96.46 ms
96.16 ms
ΔR/R0
0
1
2
3
4
5
6
0
5
10

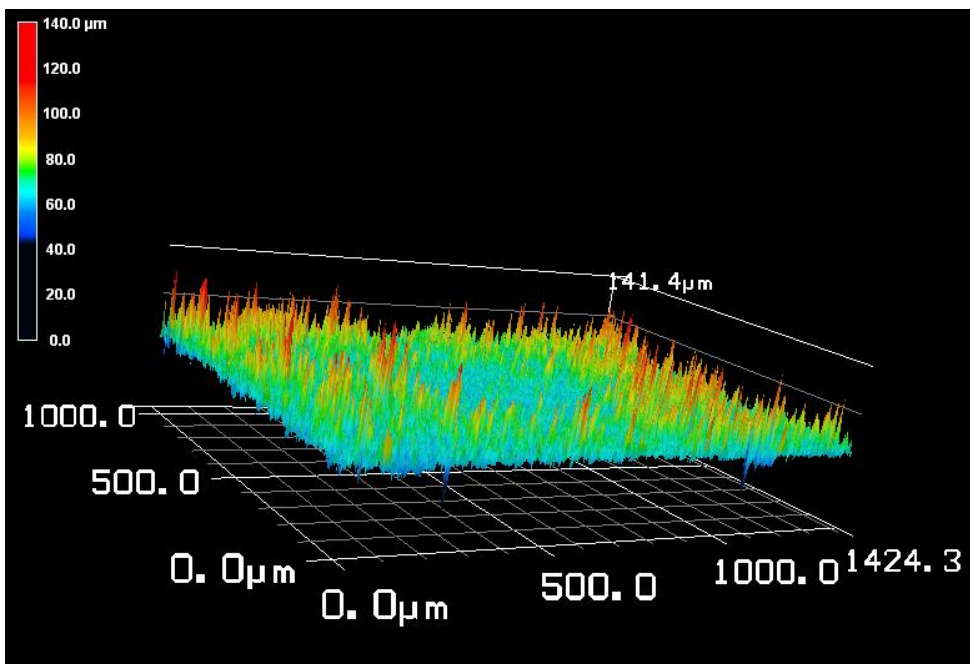

(a)
1:0 (LP)
1:0 (HP)
First working range (%)
Primary GF
Ultrasonic duration (Min.)
(b)
8:1 (LP)
4:1 (LP)
2.667:1 (LP)
2:1 (LP)
First working range (%)
Primary GF
Ultrasonic duration (Min.)
(c)
8:1 (HP)
4:1 (HP)
2.667:1 (HP)
2:1 (HP)
First working range (%)
Primary GF
Ultrasonic duration (Min.)

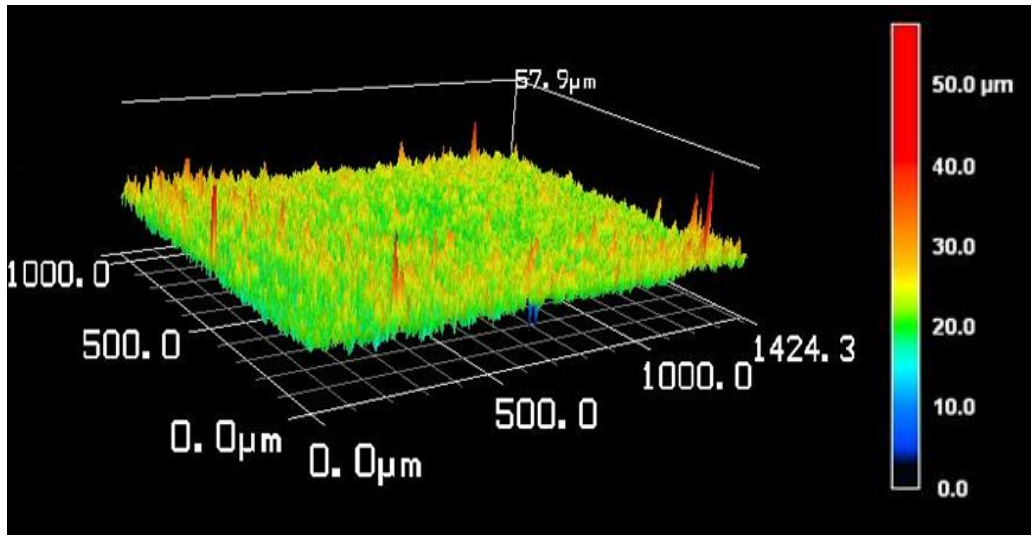

120. 1µm
500. 0
1000. 0
1424. 3
µm

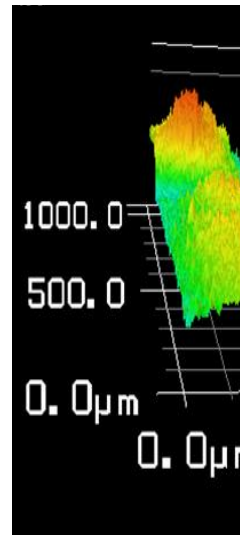

220.0 µm
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
220. 1µm
1000. 0
500. 0
0. 0µm
0. 0µm
500. 0
1000. 0
1424. 3

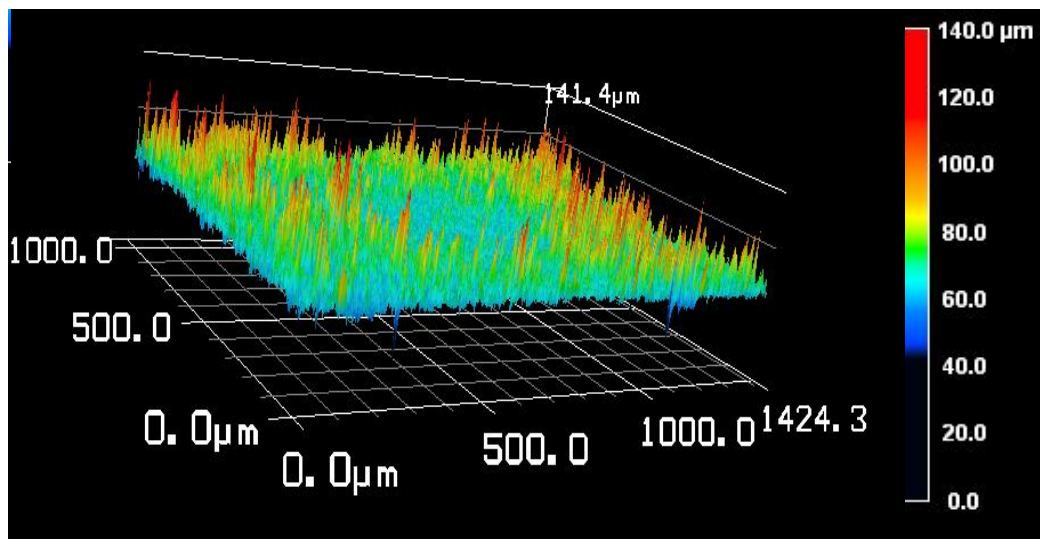
200.0 µm
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1000. 0
500. 0
0. 0

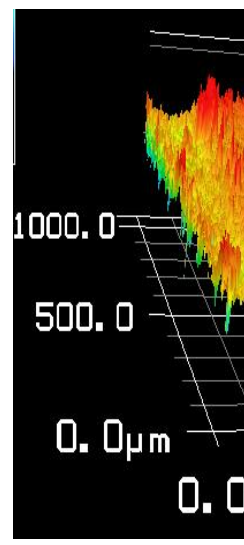

160.0 µm
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
171. 1µm
1000. 0
500. 0
0. 0µm
0. 0µm
500. 0
1000. 0
1424. 3

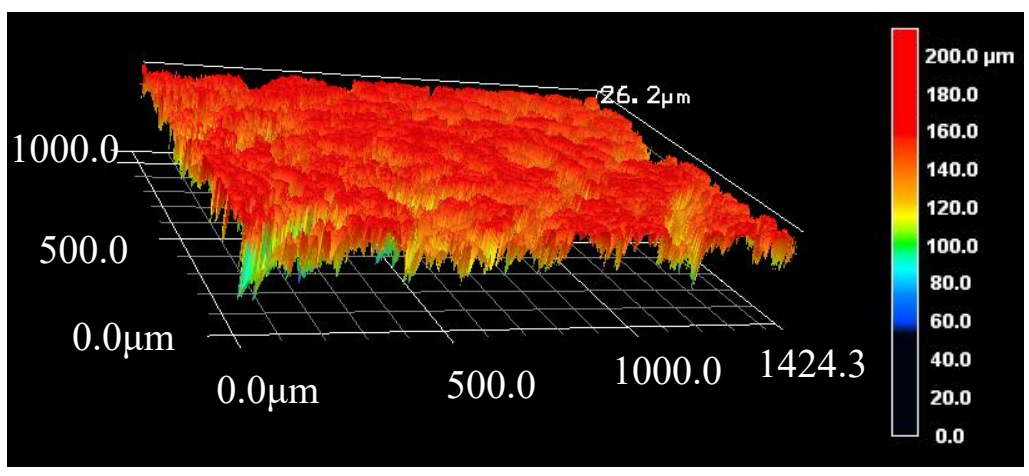

140.0 µm
120.0
100.0
80.0
60.0
40.0
20.0
0.0
141. 4µm
1000. 0
500. 0
0. 0µm
0. 0µm
500. 0
1000. 0
1424. 3

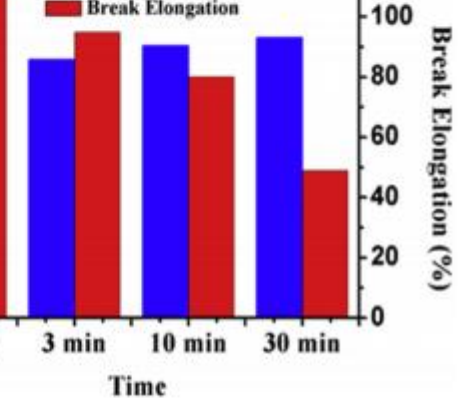

57.9µm
50.0 µm
40.0
30.0
20.0
10.0
0.0
1000.0
500.0
0.0µm
0.0µm
500.0
1000.0
1424.3


1000.0
500.0
0.0µm

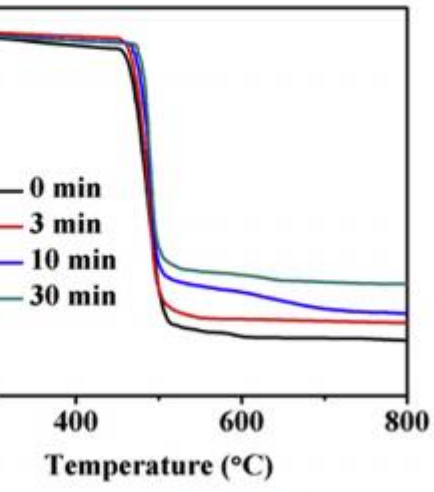

141.4µm
140.0 µm
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1000.0
500.0
0.0µm
0.0µm
500.0
1000.0
1424.3


1000.0
500.0
0.0µm

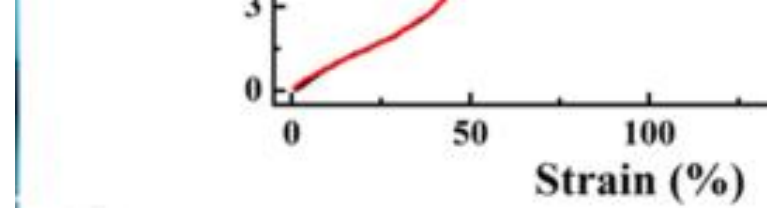

26.2µm
200.0 µm
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1000.0
500.0
0.0µm
0.0µm
500.0
1000.0
1424.3



of the PVDF nanofibrous films (a) Stress-strain curv
ength and break elongation.



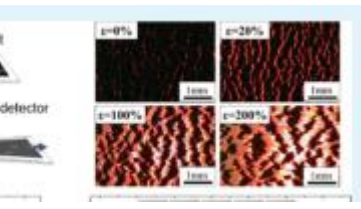
electrospun PVDF and PVDF/MWNTs nanofibrous filn

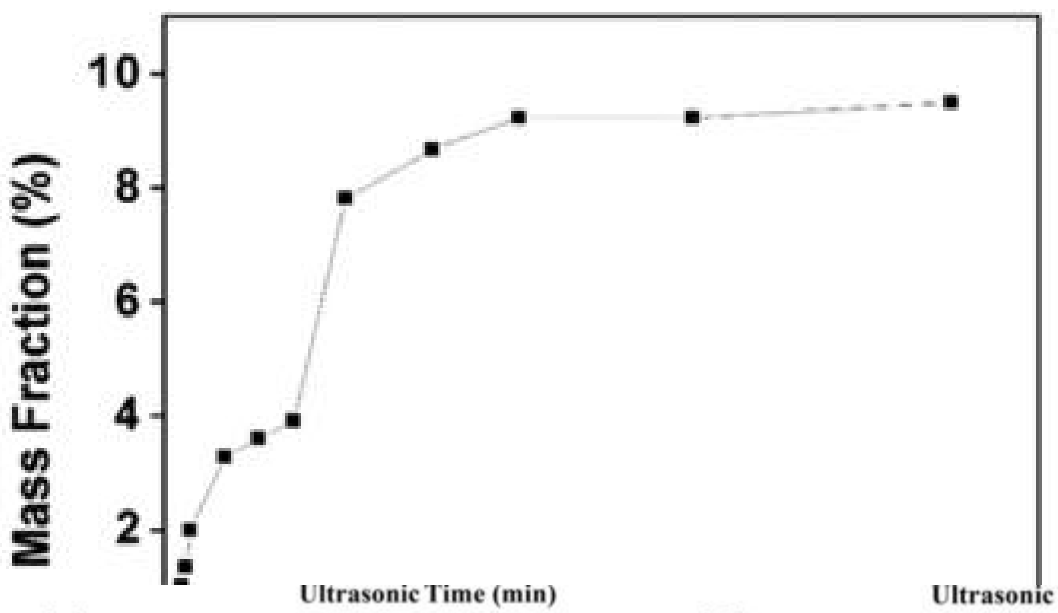


a

c

Gauge





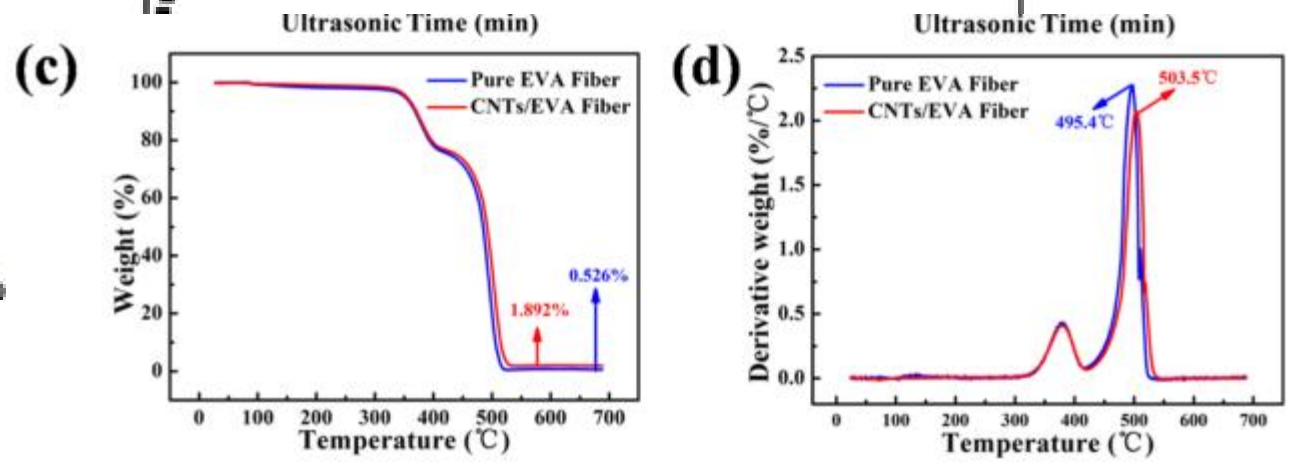


Fig. 4. Th

Figure S

Ecoflex

transmitt

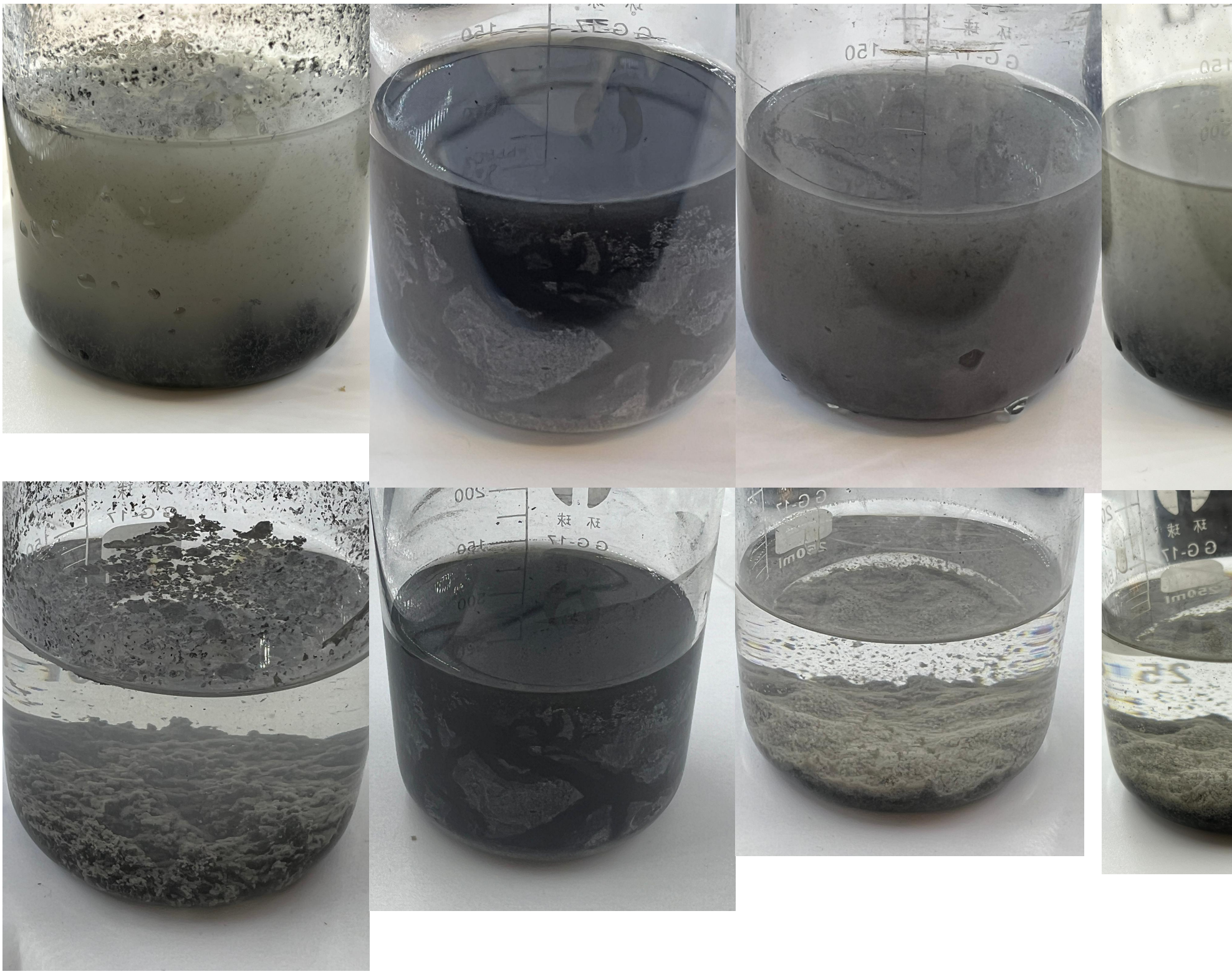
different

sensors

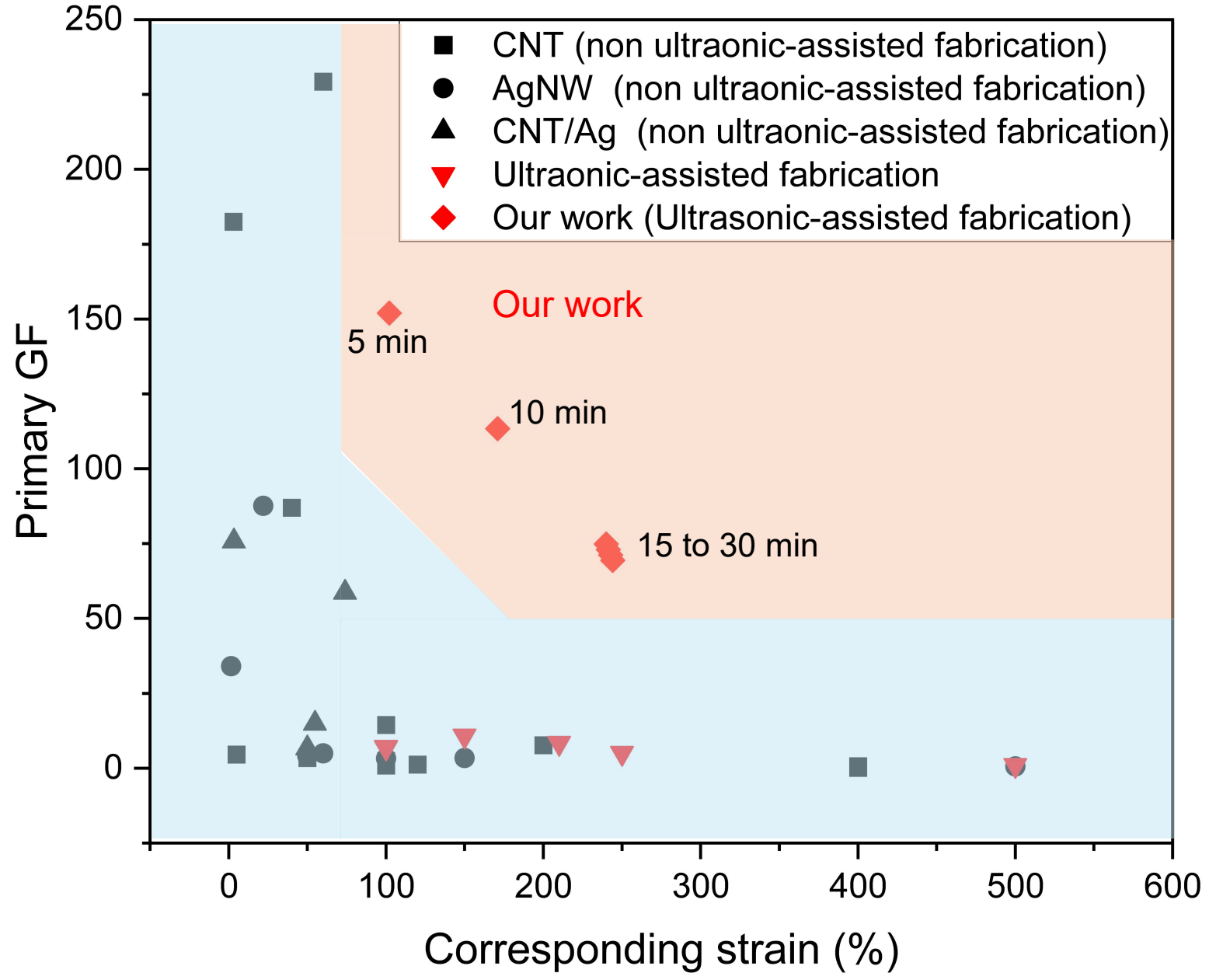
Ecoflex

of ε=25

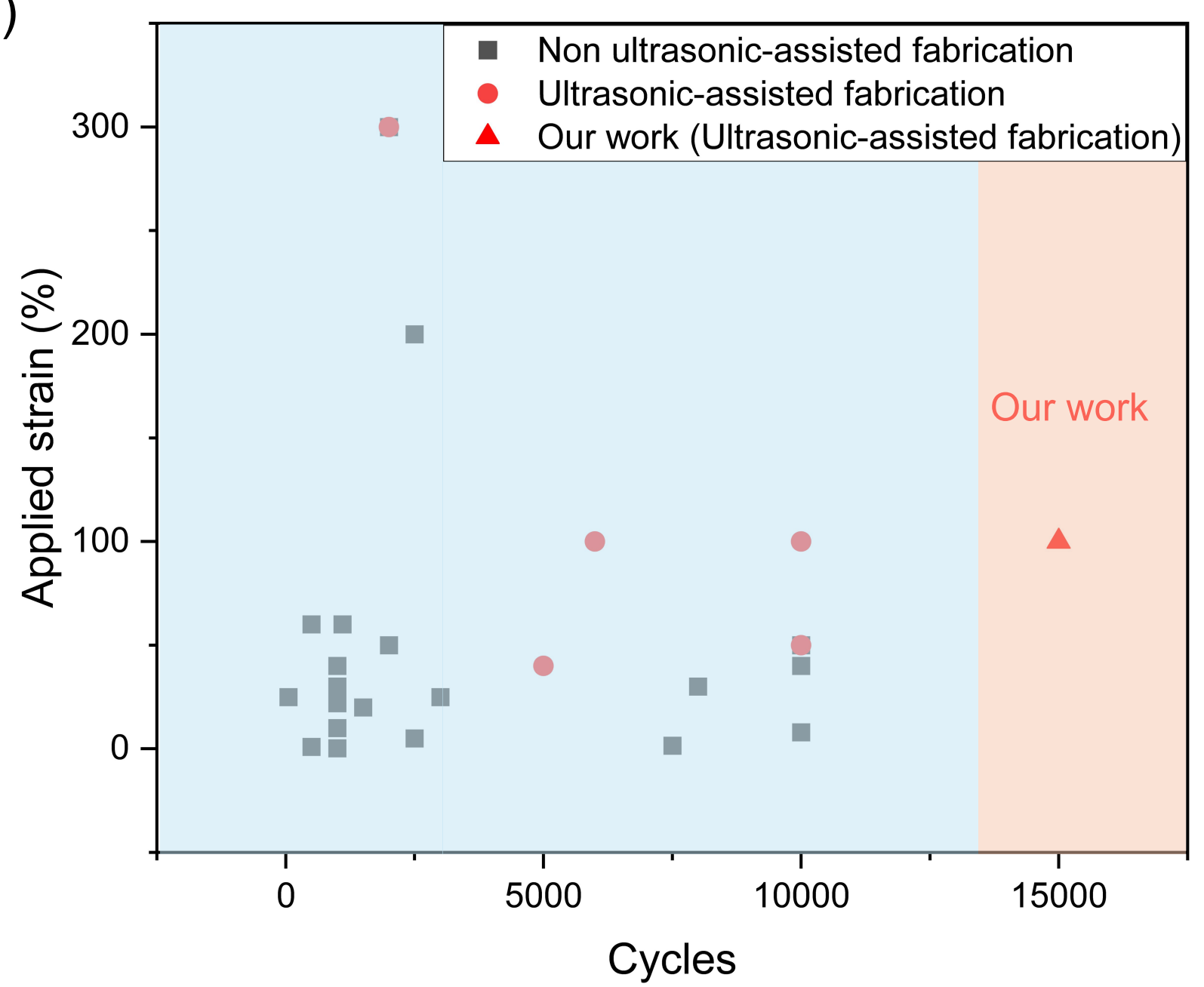
DI water **DI water + Triton X-100** **IPA** **IPA + T**



(*)

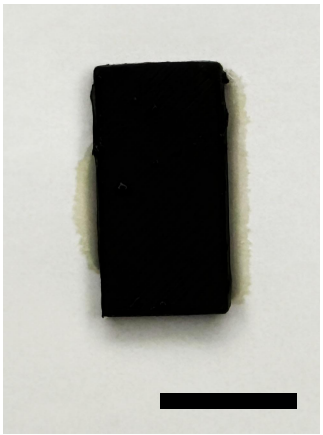

CNT (non ultraonic-assisted fabrication)
AgNW (non ultraonic-assisted fabrication)
CNT/Ag (non ultraonic-assisted fabrication)
Ultraonic-assisted fabrication
Our work (Ultrasonic-assisted fabrication)
Our work
5 min
10 min
15 to 30 min
Primary GF
Corresponding strain (%)
250
200
150
100
50
0
0
100
200
300
400
500
600

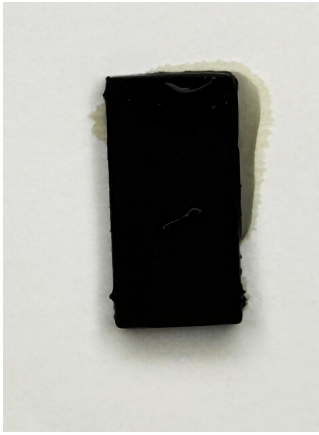
(b)


Non ultrasonic-assisted fabrication
Ultrasonic-assisted fabrication
Our work (Ultrasonic-assisted fabrication)
Our work
Applied strain (%)
Cycles
300
200
100
0
0
5000
10000
15000

Ecoflex+DI water

PDMS+DI water

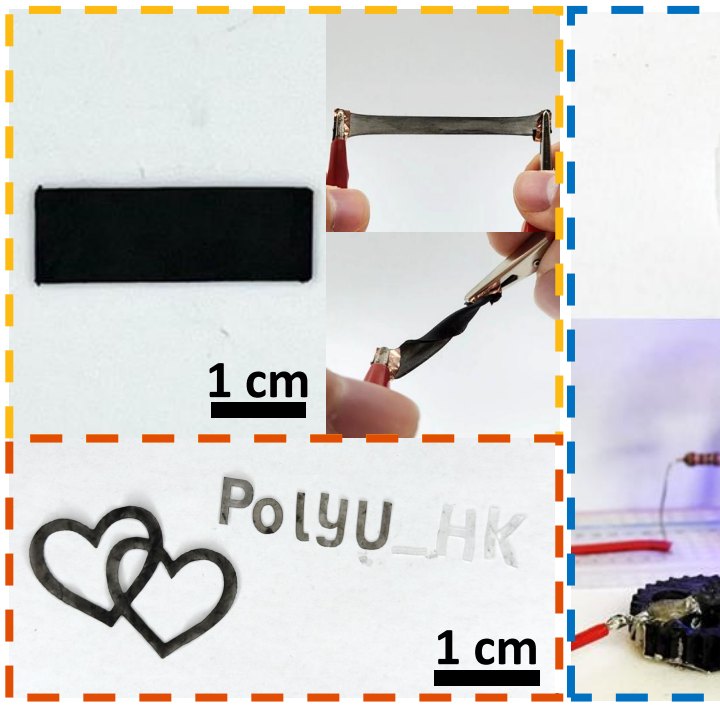


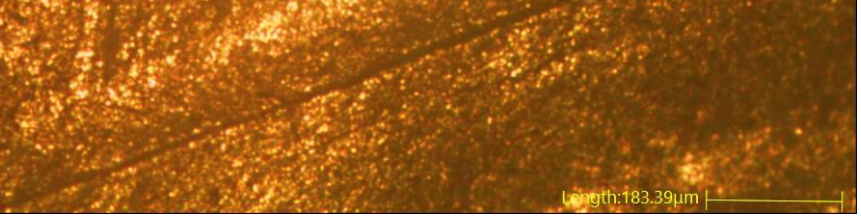


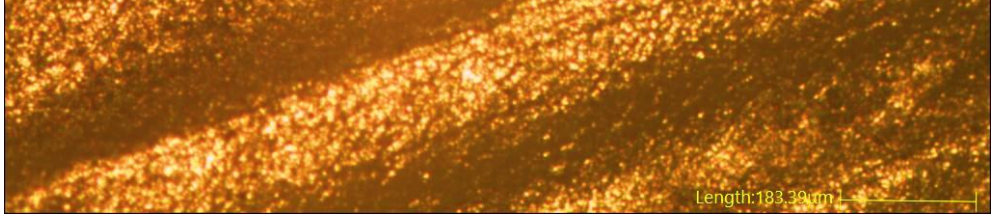
TPU+DI water

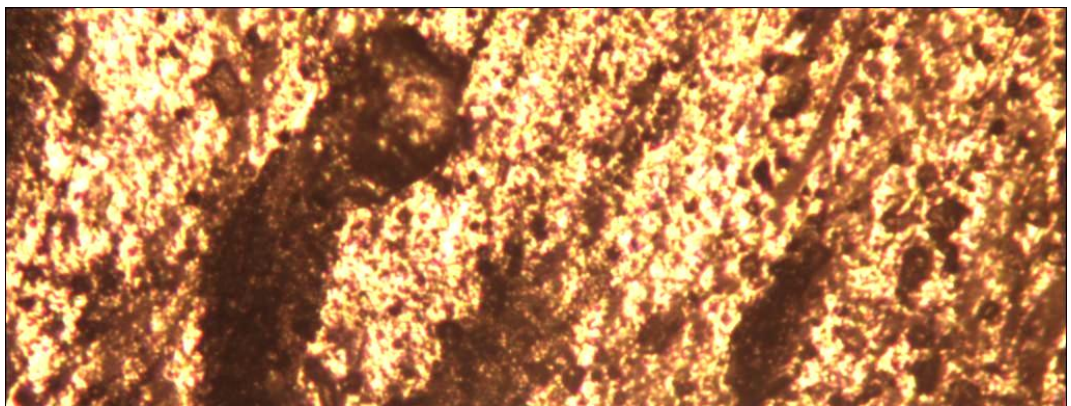
Ecoflex+Ethanol

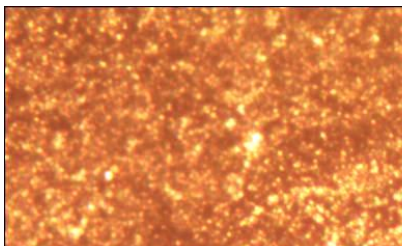
Compare

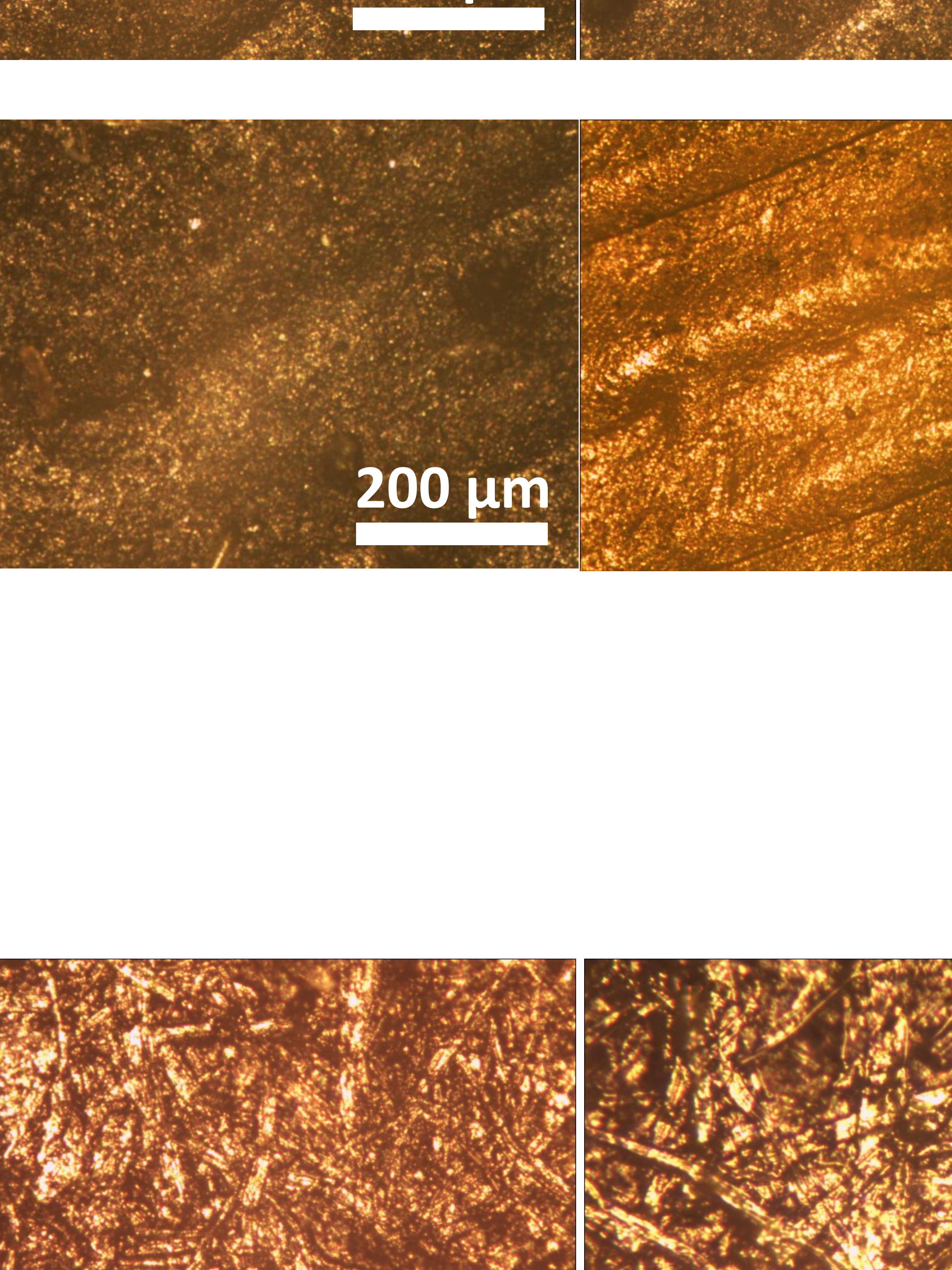


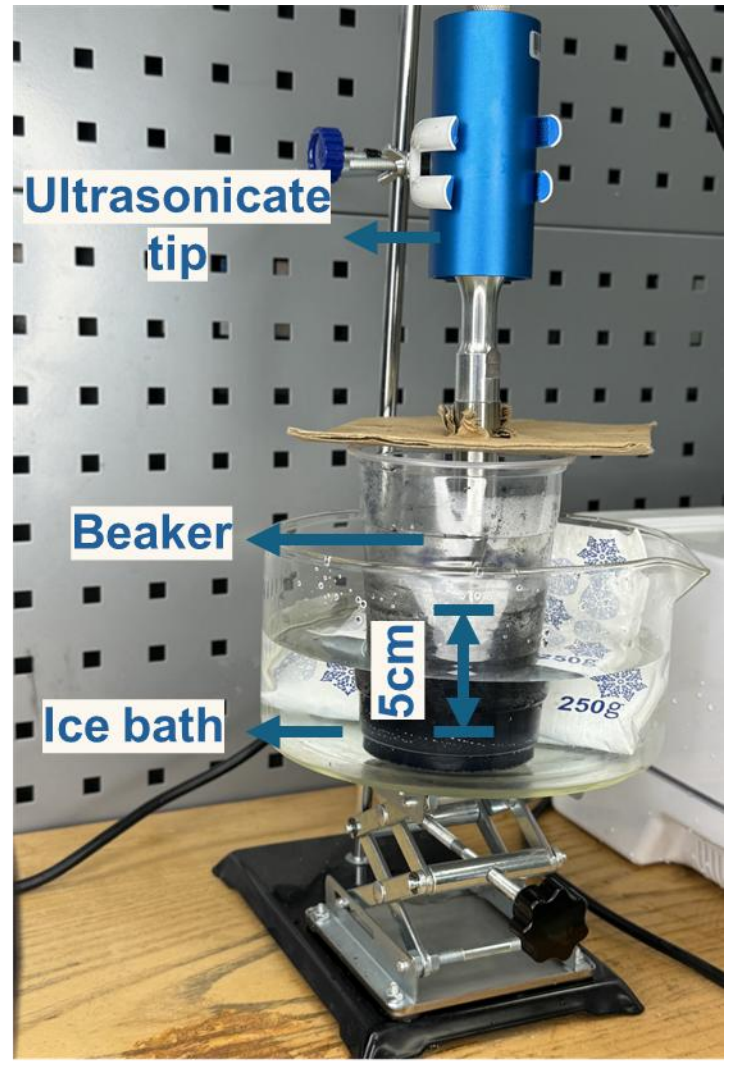

Length:183.39μm

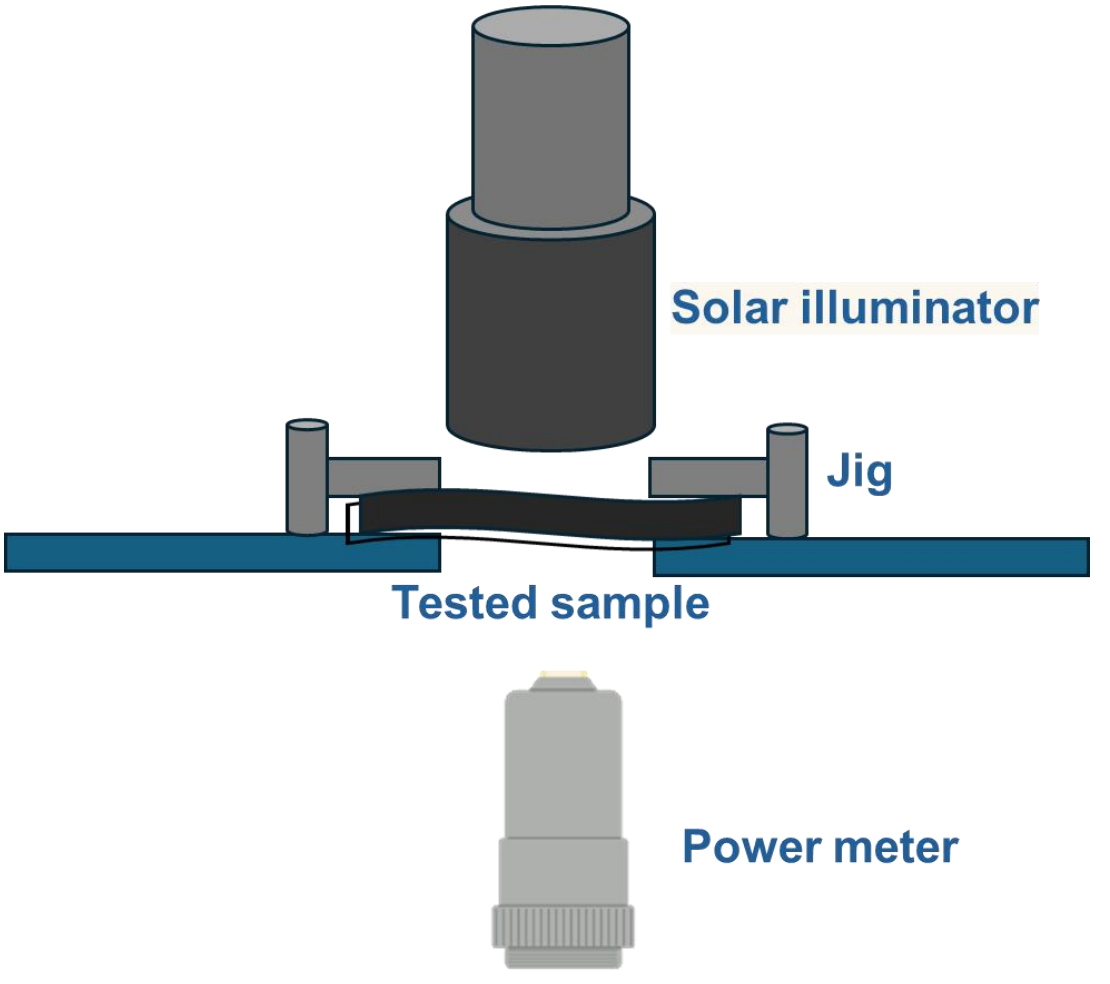

Length:183.39μm

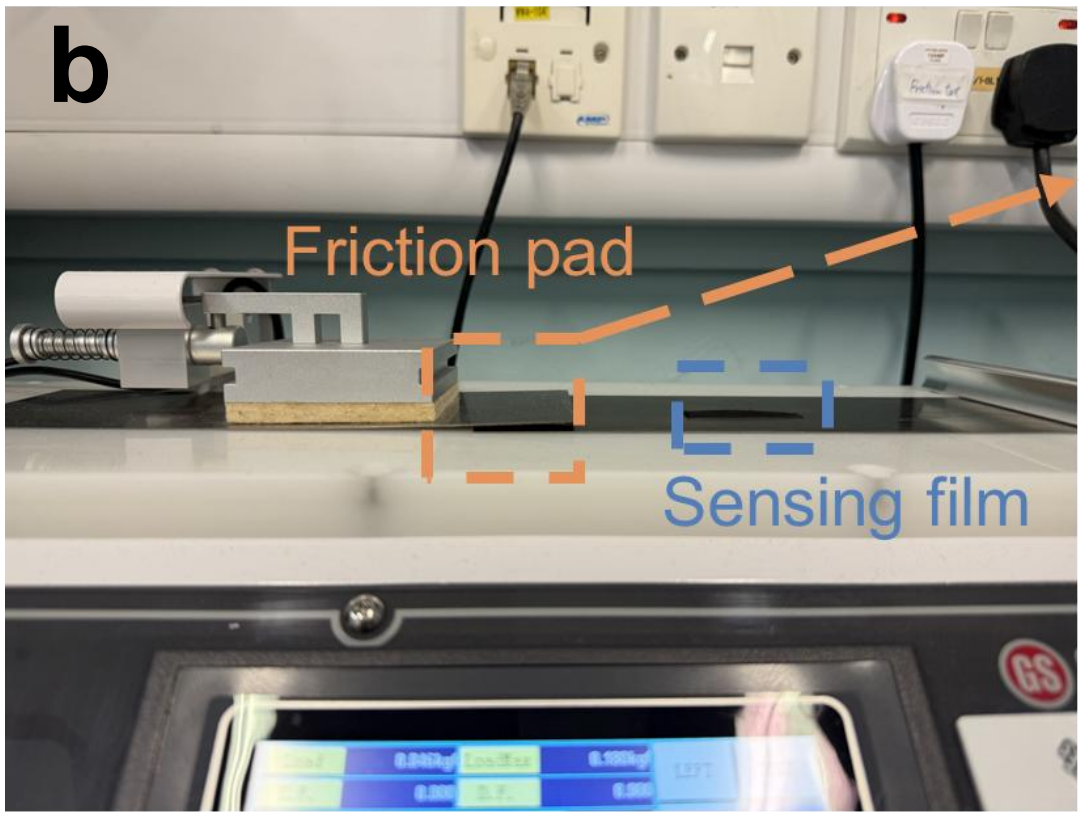


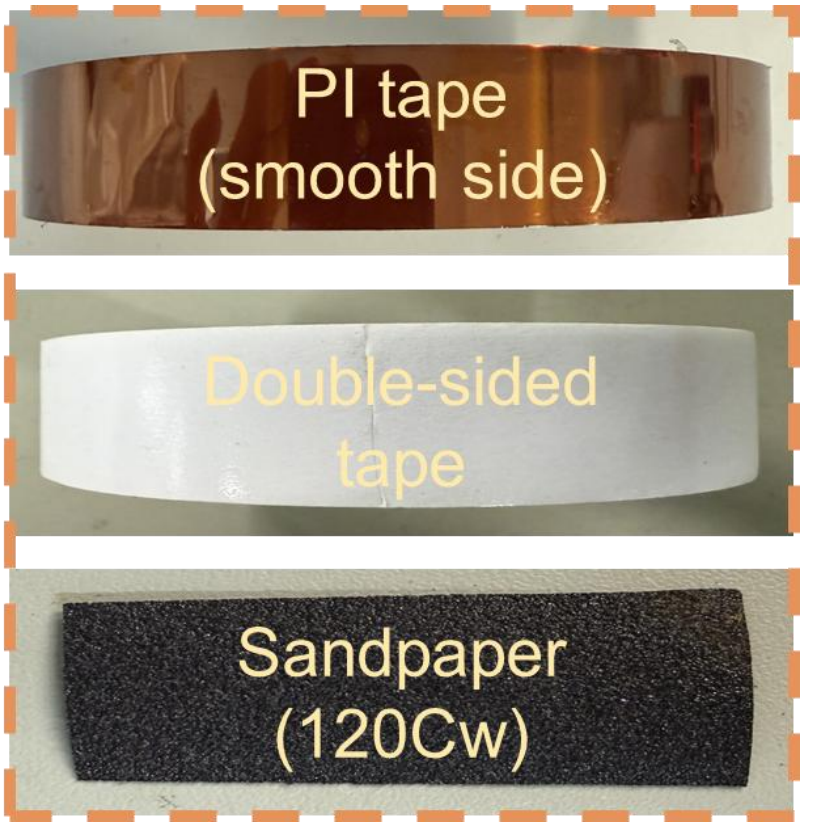


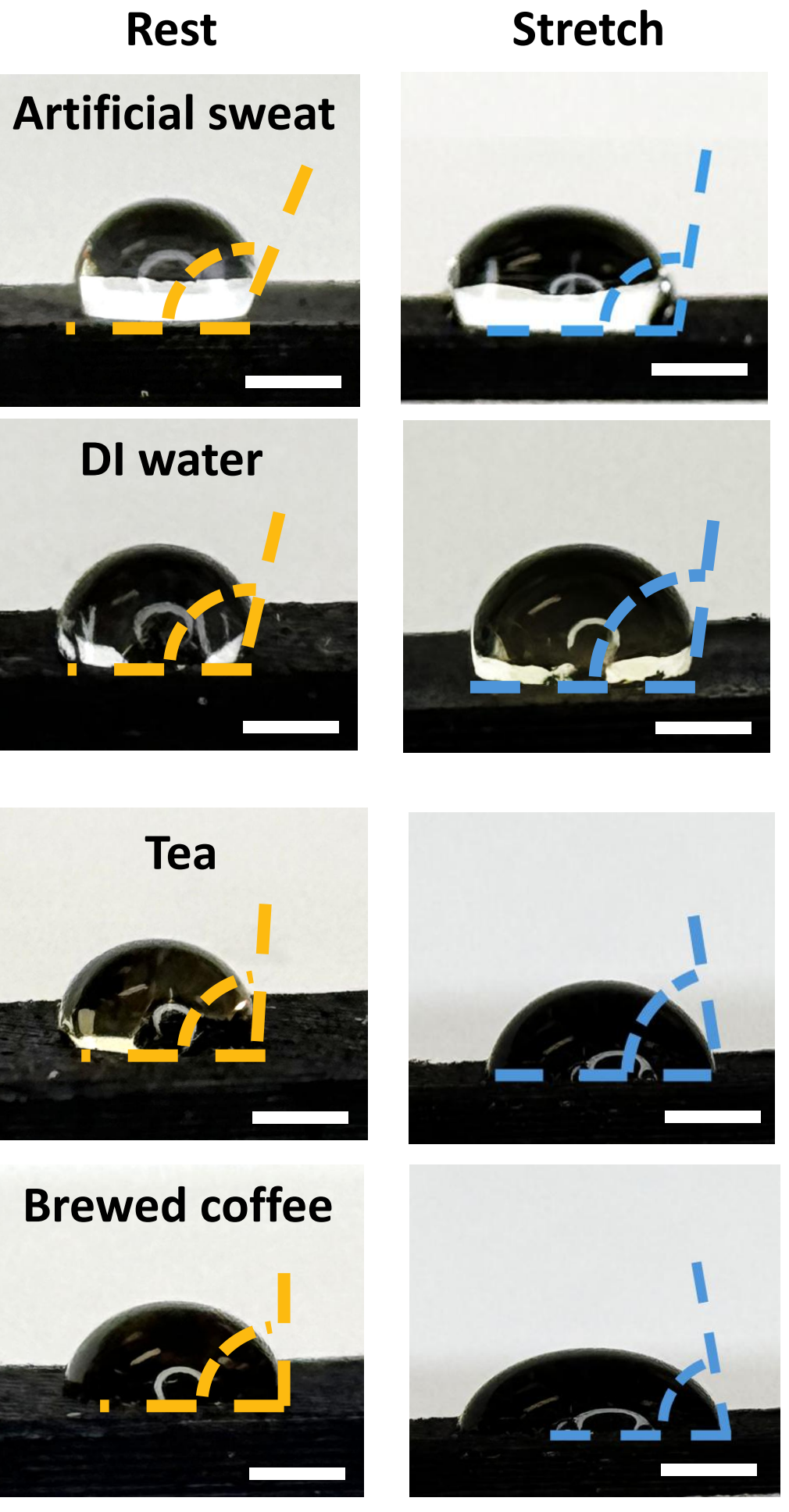

200 µm

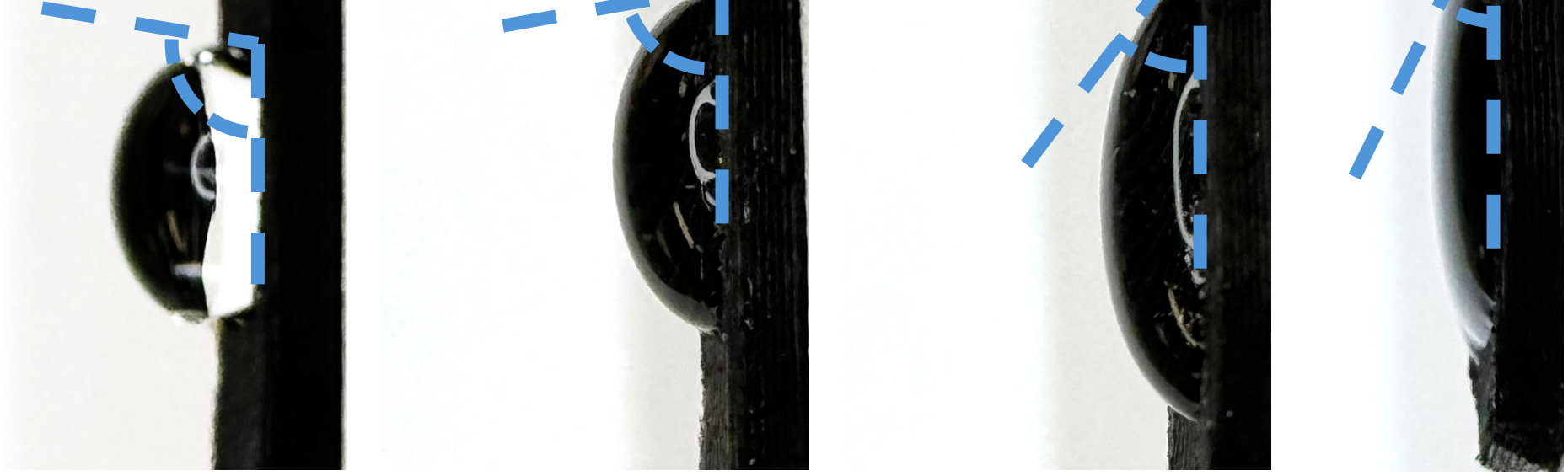

a
Ultrasonicate tip
Beaker
Ice bath
5cm
250g

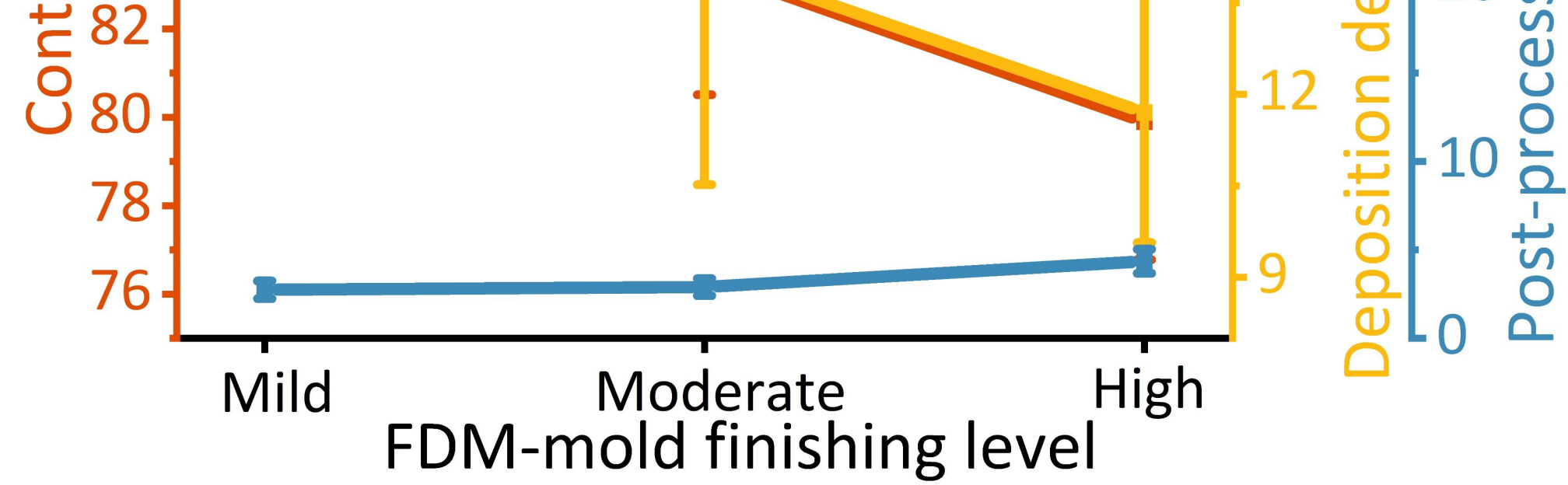

c
Solar illuminator
Jig
Tested sample
Power meter

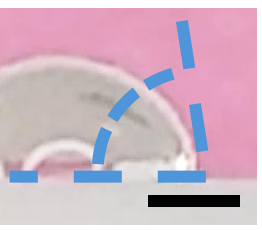

b
Friction pad
Sensing film

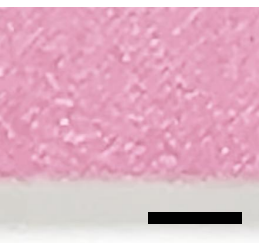

PI tape
(smooth side)
Double-sided
tape
Sandpaper
(120Cw)

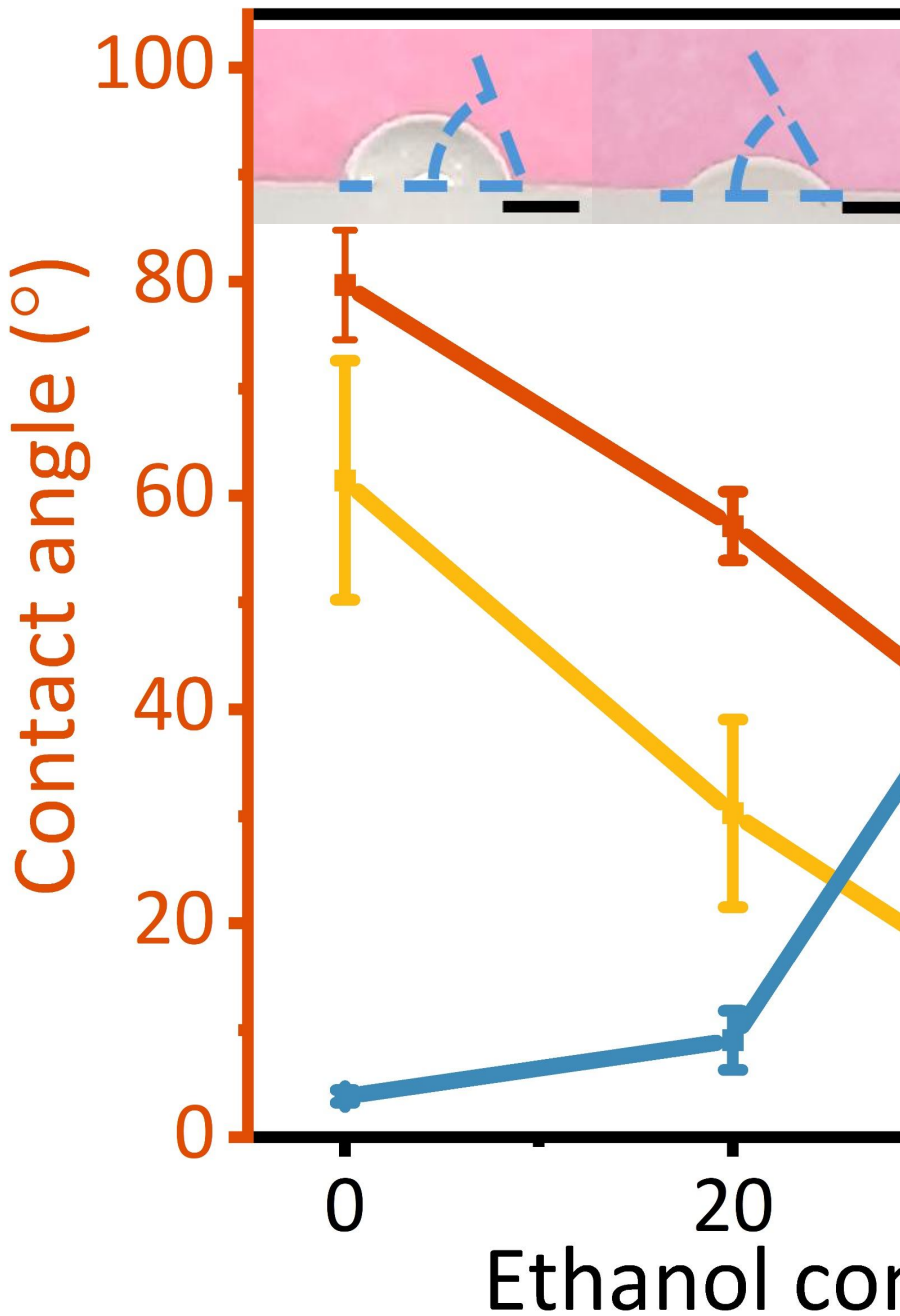

Rest
Stretch
Artificial sweat
DI water
Tea
Brewed coffee



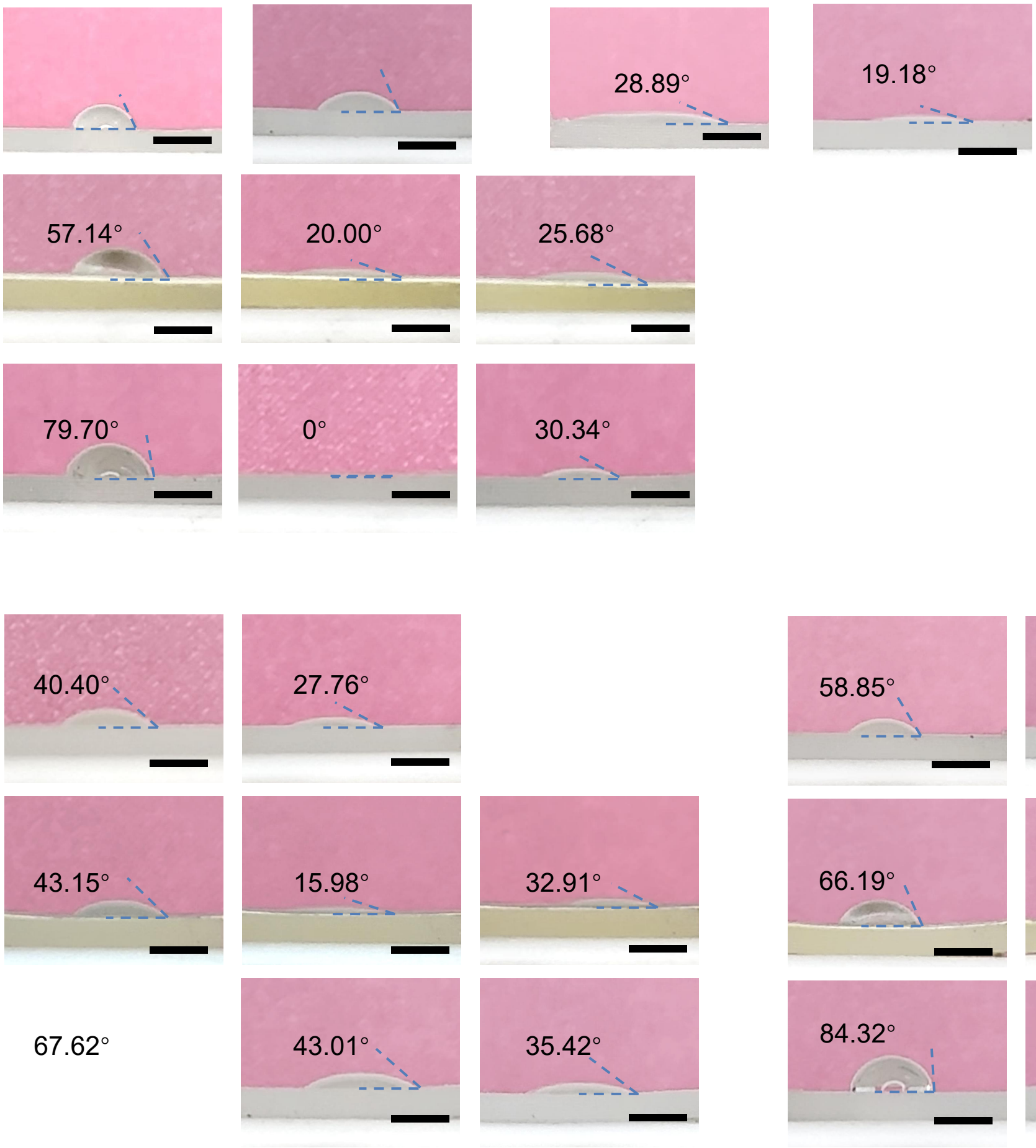

Cont
82
80
78
76
12
9
Deposition de
10
0
Post-process
Mild
Moderate
High
FDM-mold finishing level



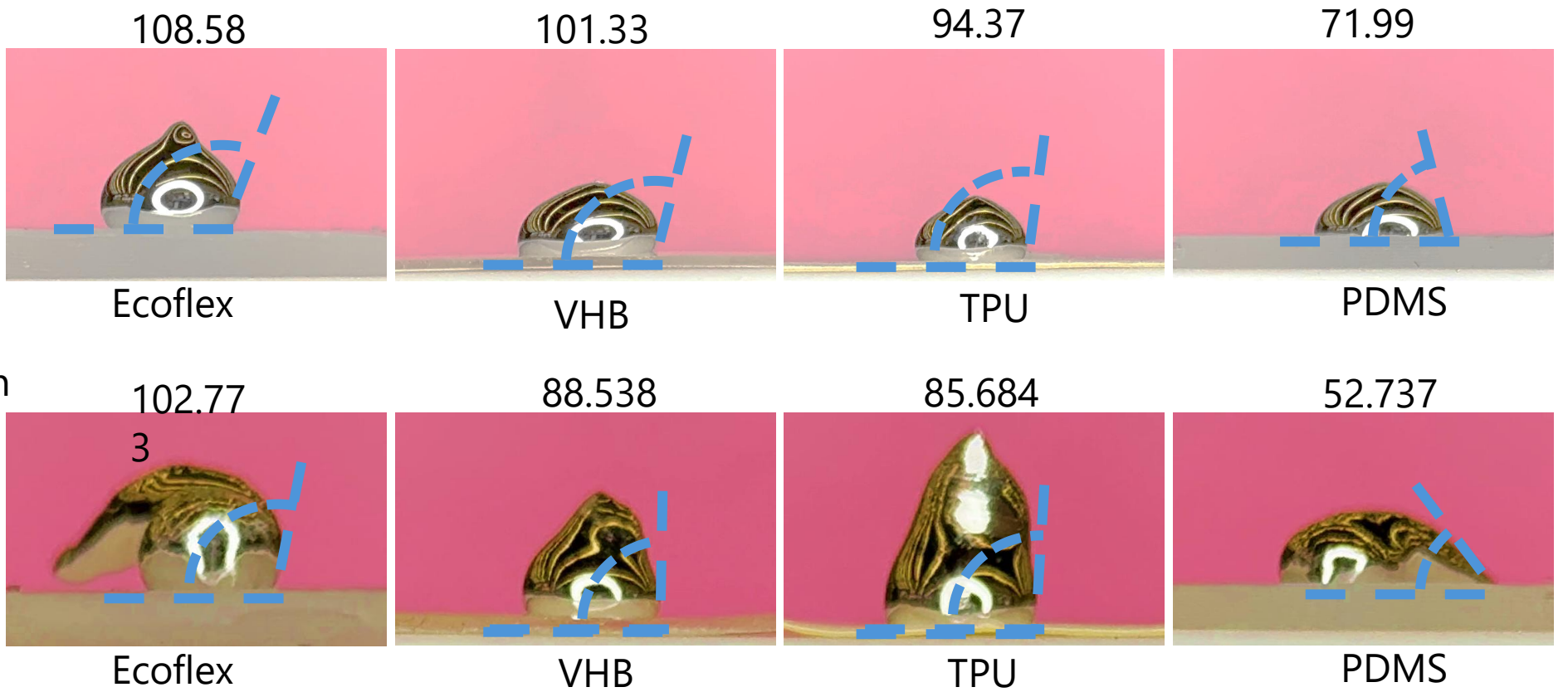



100
80
60
40
20
0
Contact angle (°)
0
20
Ethanol con

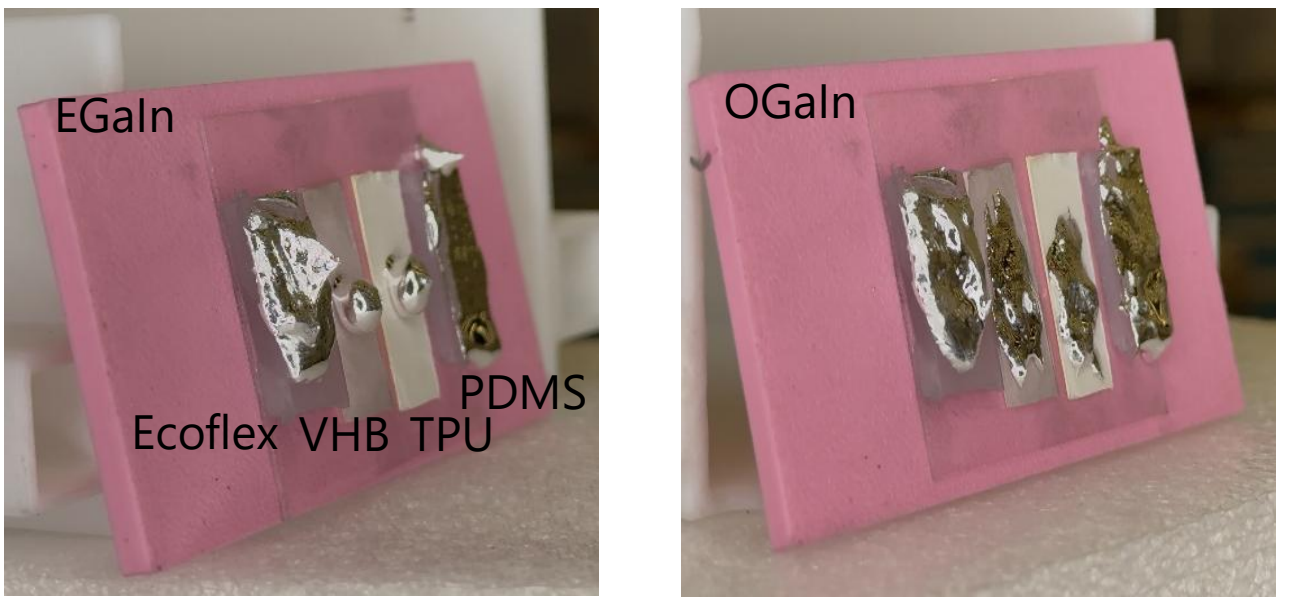
20
m2)
%)
Anhydrous ethanol

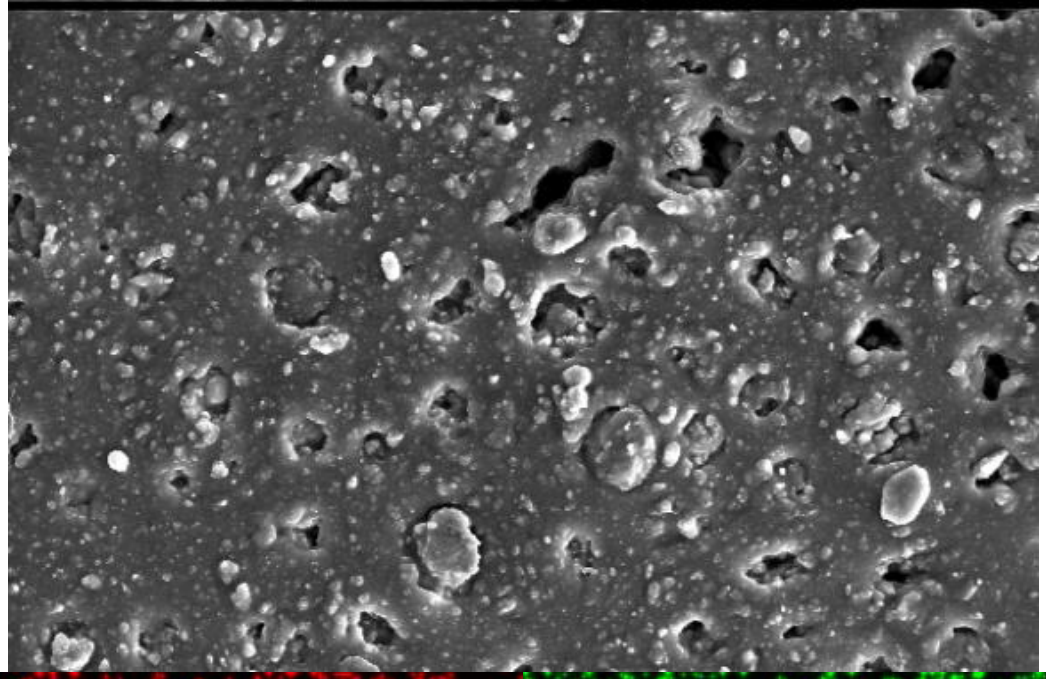

28.89°
19.18°
57.14°
20.00°
25.68°
79.70°
0°
30.34°
40.40°
27.76°
58.85°
43.15°
15.98°
32.91°
66.19°
67.62°
43.01°
35.42°
84.32°

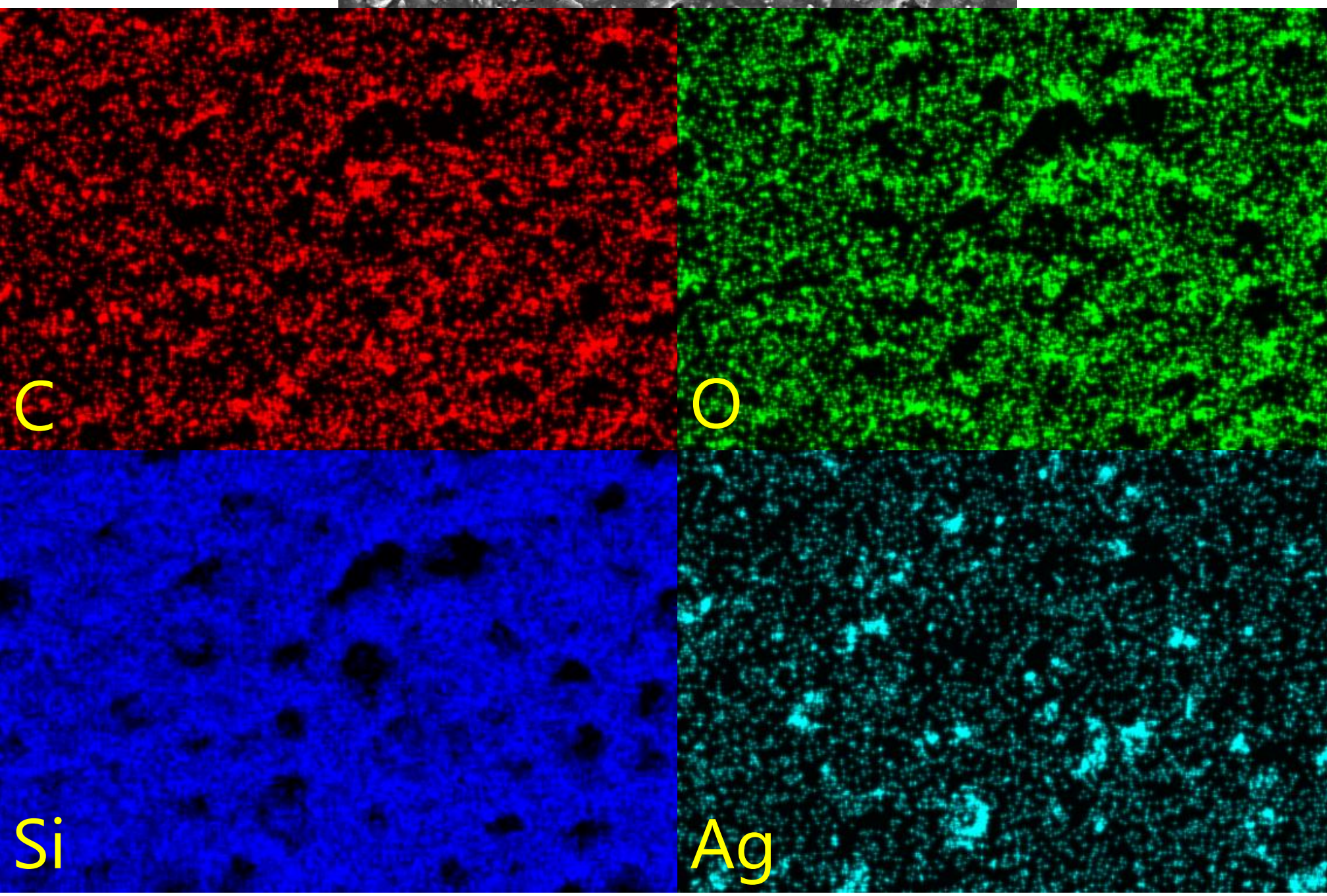
EGaIn

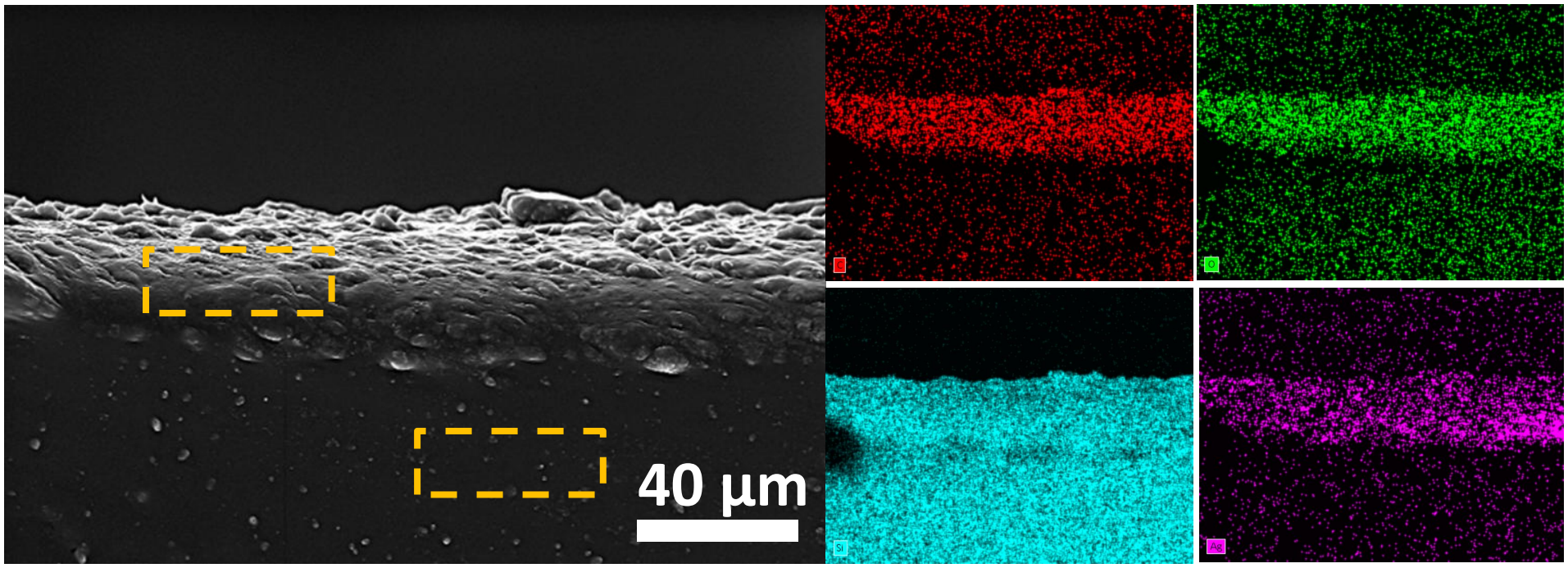


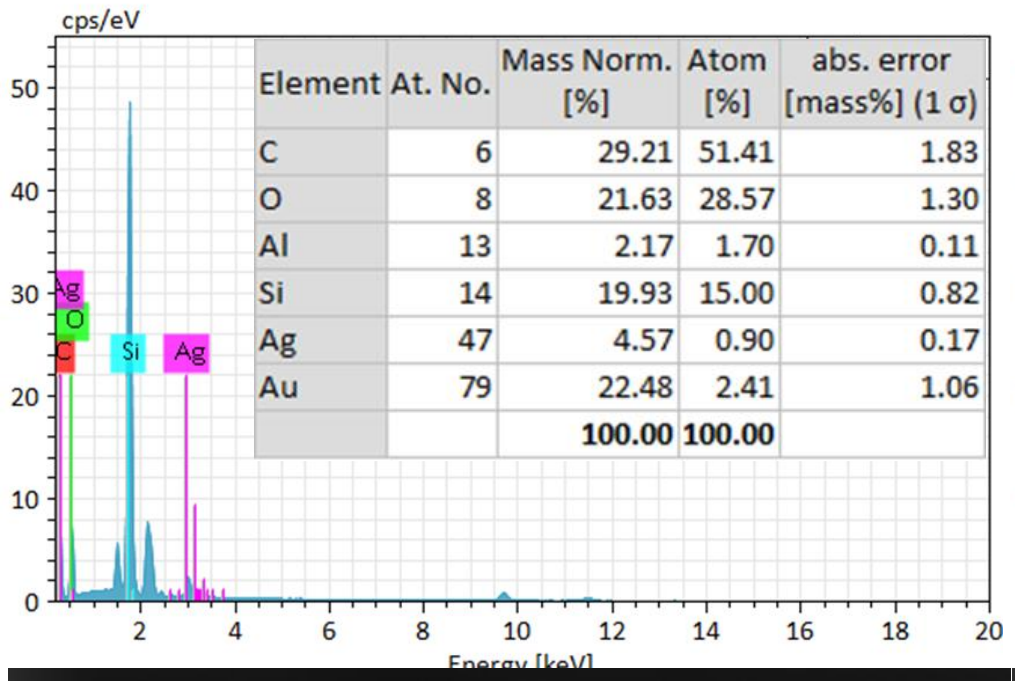
Compare



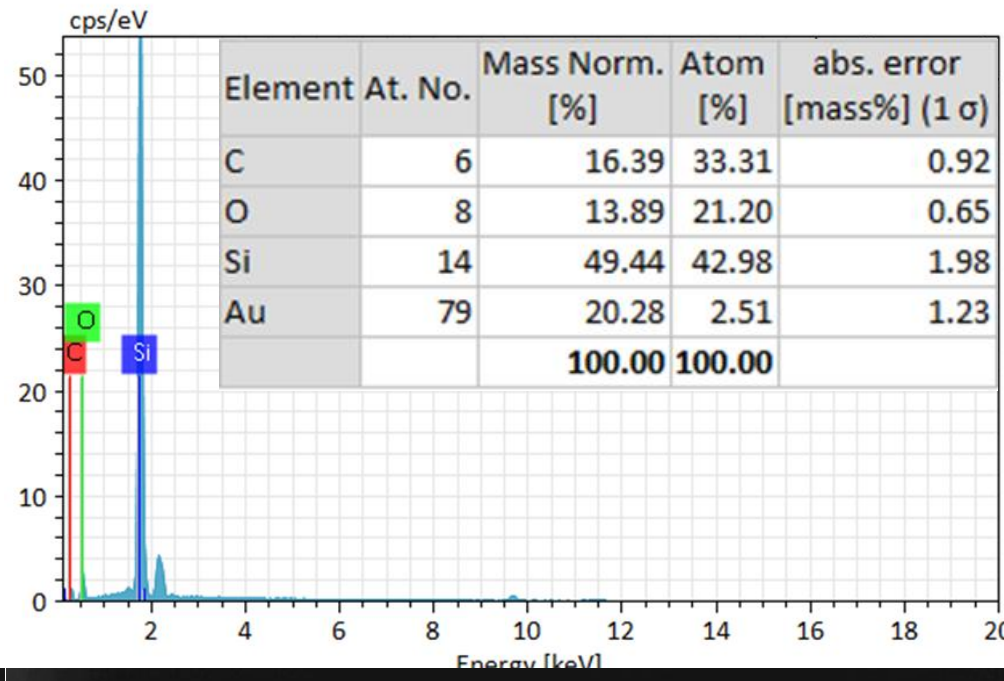



C
O
Si
Ag

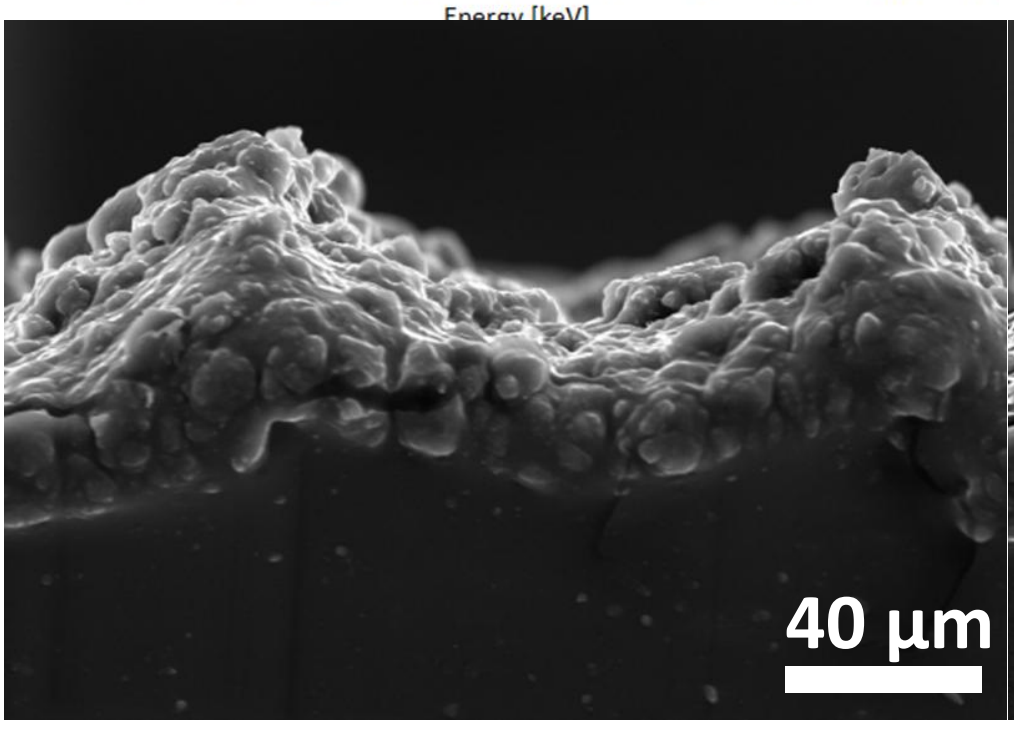


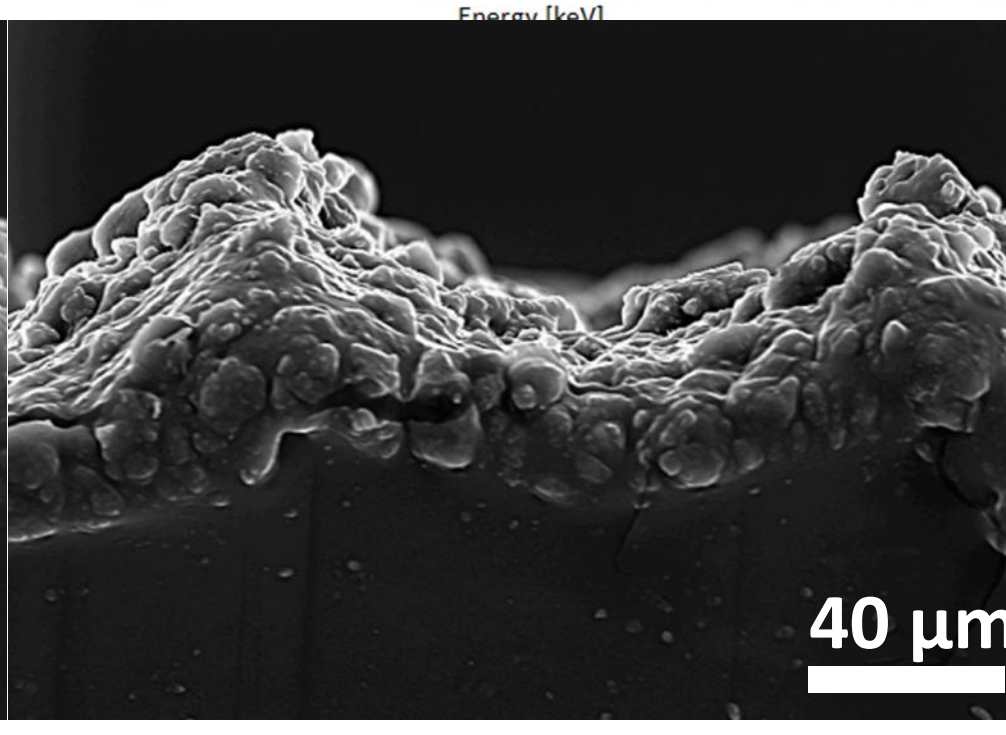


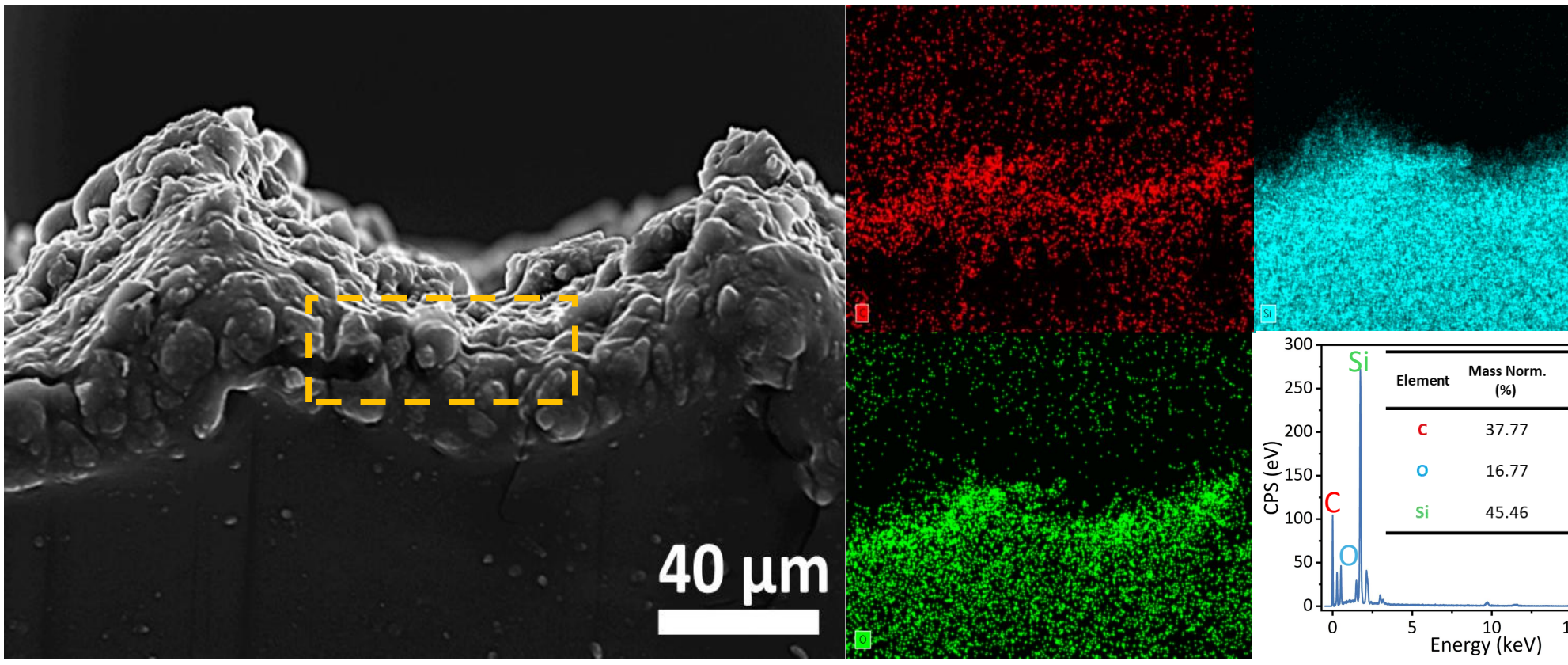
Element	At. No.	Mass Norm. [%]	Atom [%]	abs. error [mass%] (1 σ)
C	6	29.21	51.41	1.83
O	8	21.63	28.57	1.30
Al	13	2.17	1.70	0.11
Si	14	19.93	15.00	0.82
Ag	47	4.57	0.90	0.17
Au	79	22.48	2.41	1.06
		100.00	**100.00**	



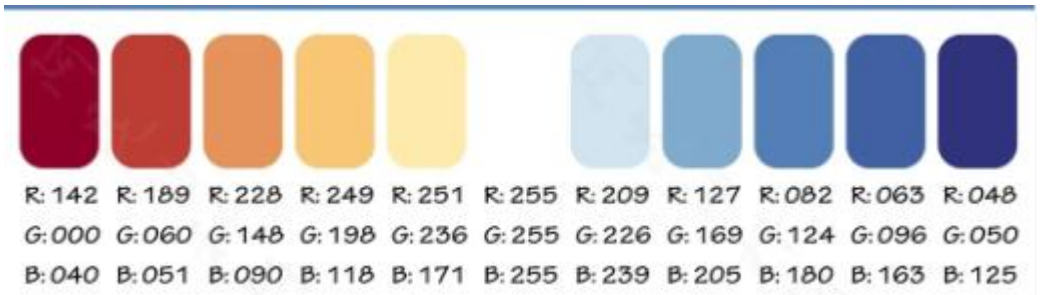
Element	At. No.	Mass Norm. [%]	Atom [%]	abs. error [mass%] (1 σ)
C	6	16.39	33.31	0.92
O	8	13.89	21.20	0.65
Si	14	49.44	42.98	1.98
Au	79	20.28	2.51	1.23
		100.00	**100.00**	

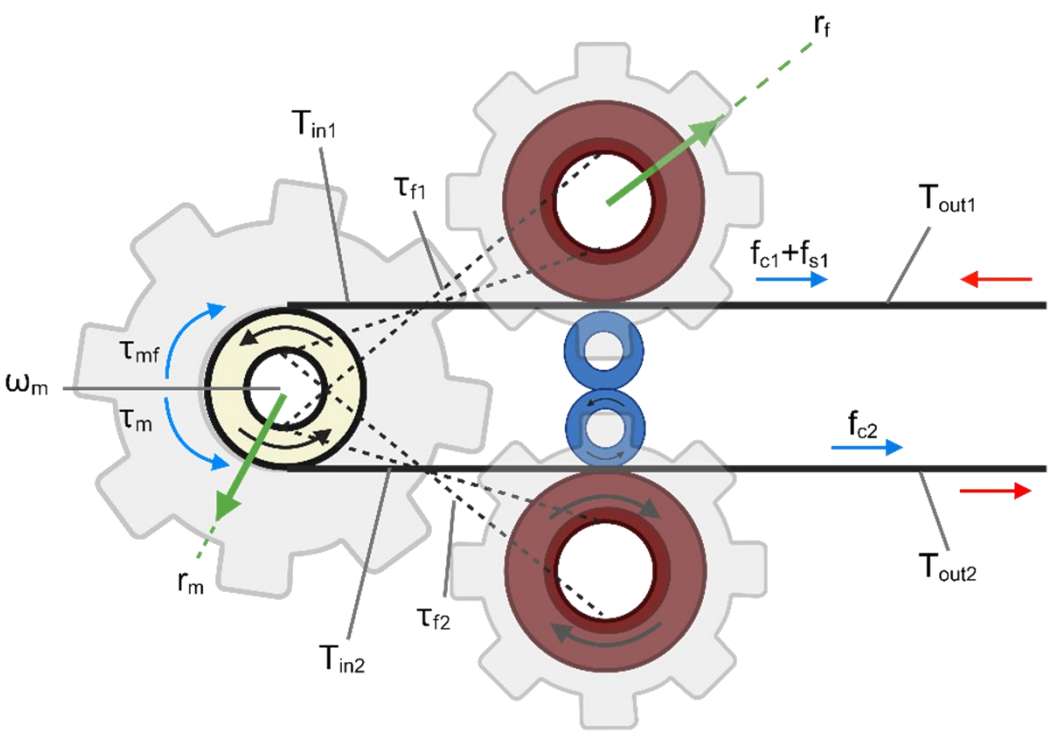




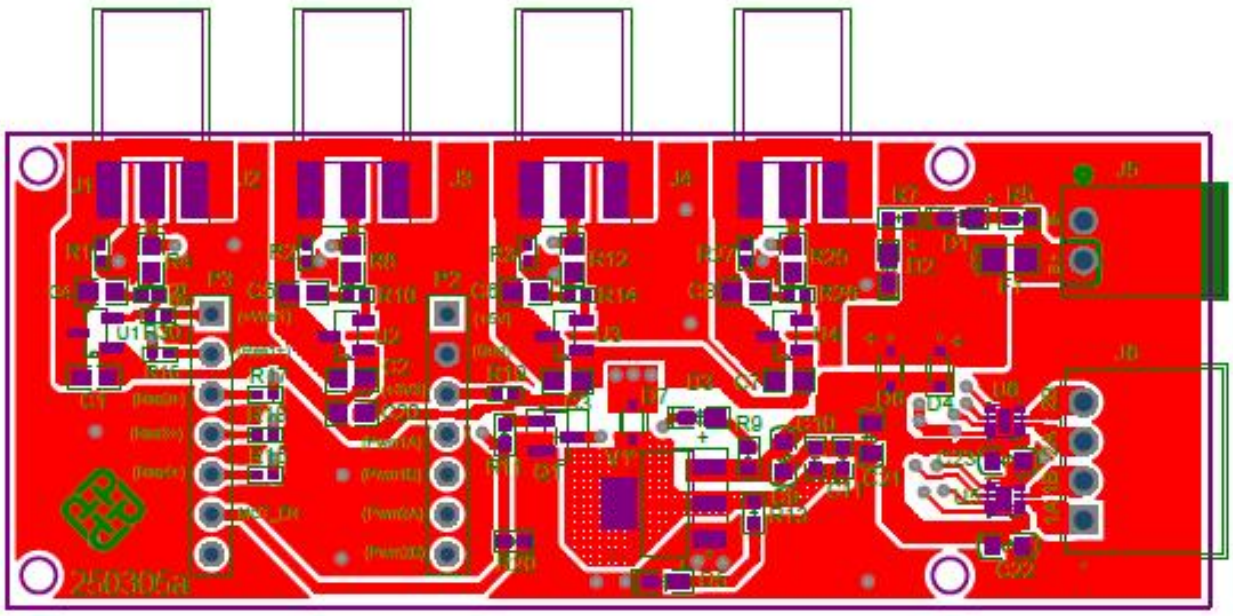

40 µm
C
Si
O
Si
C
O
CPS (eV)
Energy (keV)
300
250
200
150
100
50
0
0
5
10
Element | Mass Norm. (%)
C | 37.77
O | 16.77
Si | 45.46

Mechanical

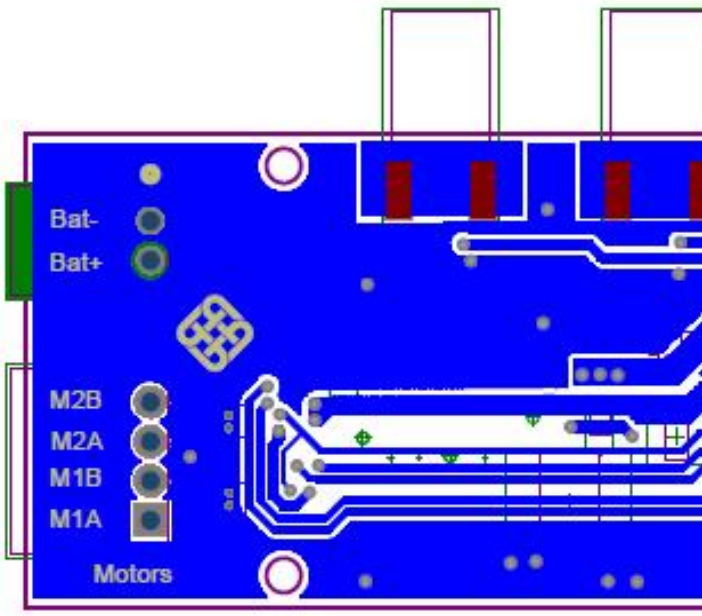

R: 142 R: 189 R: 228 R: 249 R: 251 R: 255 R: 209 R: 127 R: 082 R: 063 R: 048
G: 000 G: 060 G: 148 G: 198 G: 236 G: 255 G: 226 G: 169 G: 124 G: 096 G: 050
B: 040 B: 051 B: 090 B: 118 B: 171 B: 255 B: 239 B: 205 B: 180 B: 163 B: 125


r_f
T_{in1}
τ_{f1}
T_{out1}
$f_{c1}+f_{s1}$
τ_{mf}
ω_m
τ_m
f_{c2}
r_m
τ_{f2}
T_{out2}
T_{in2}

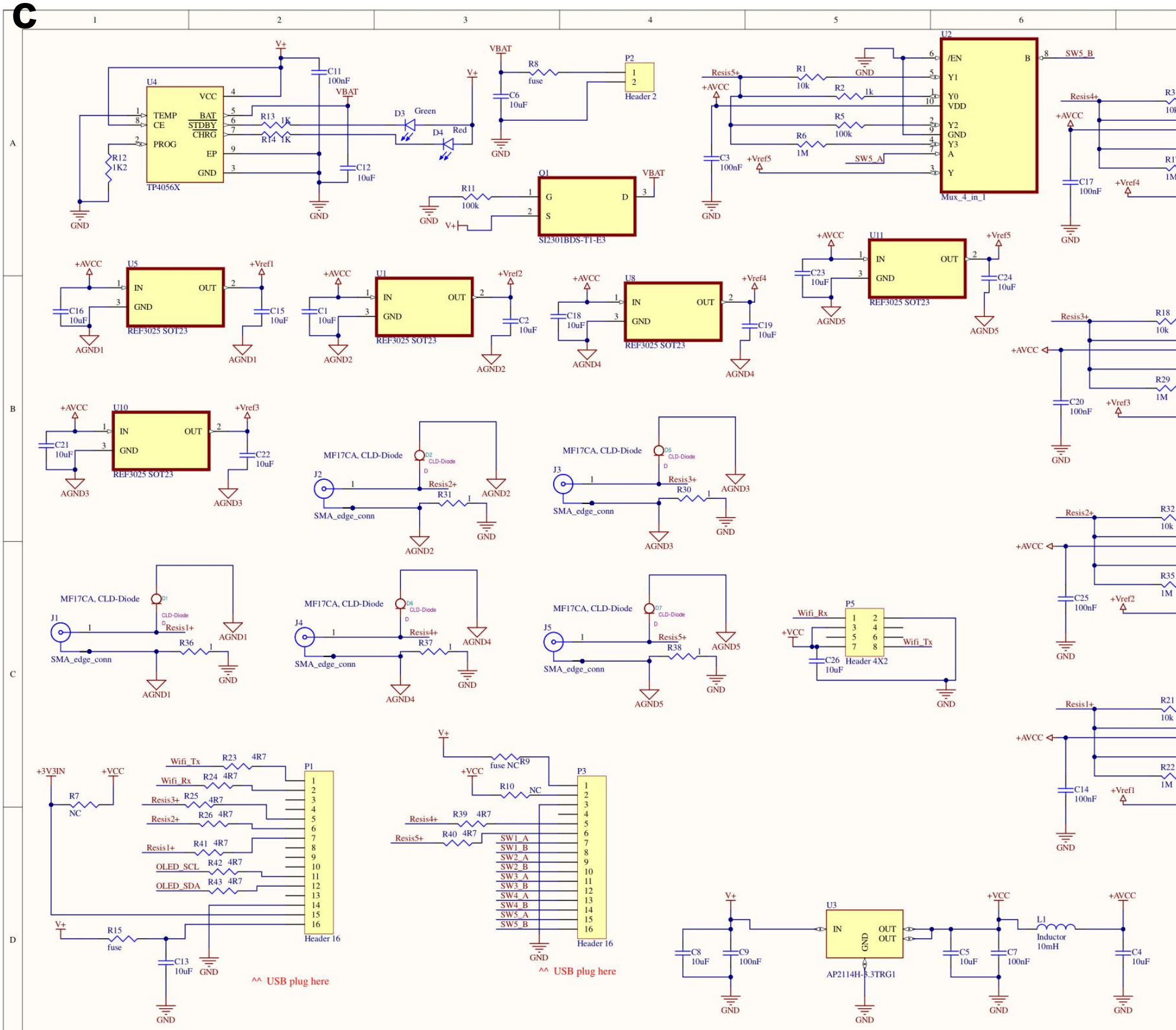
a

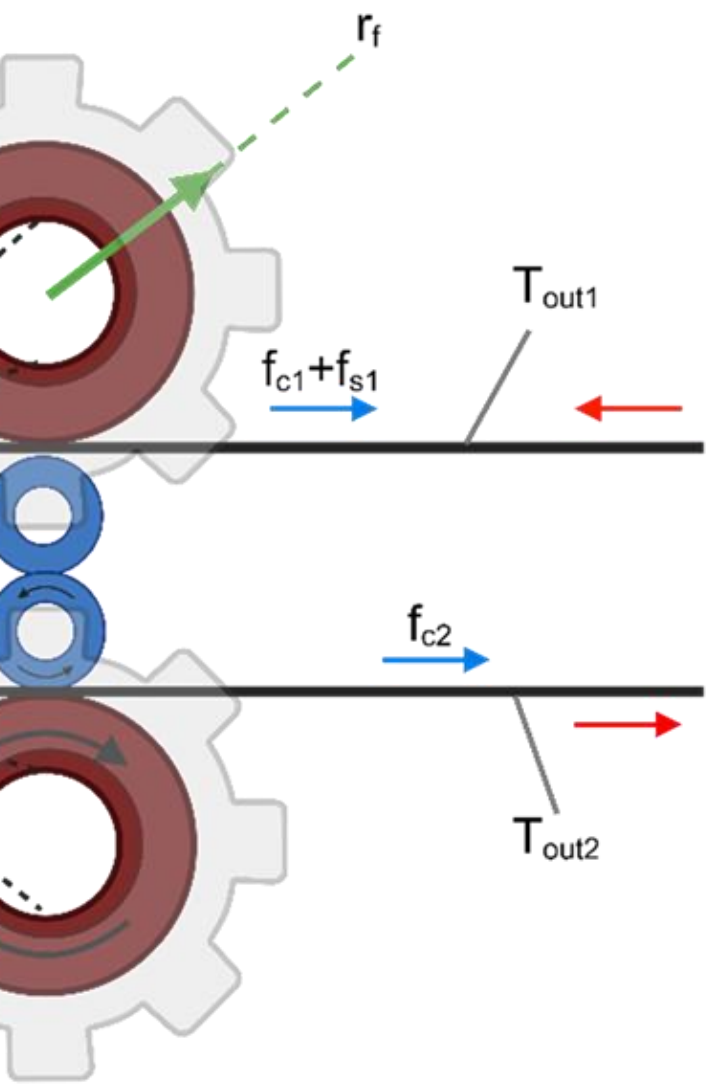


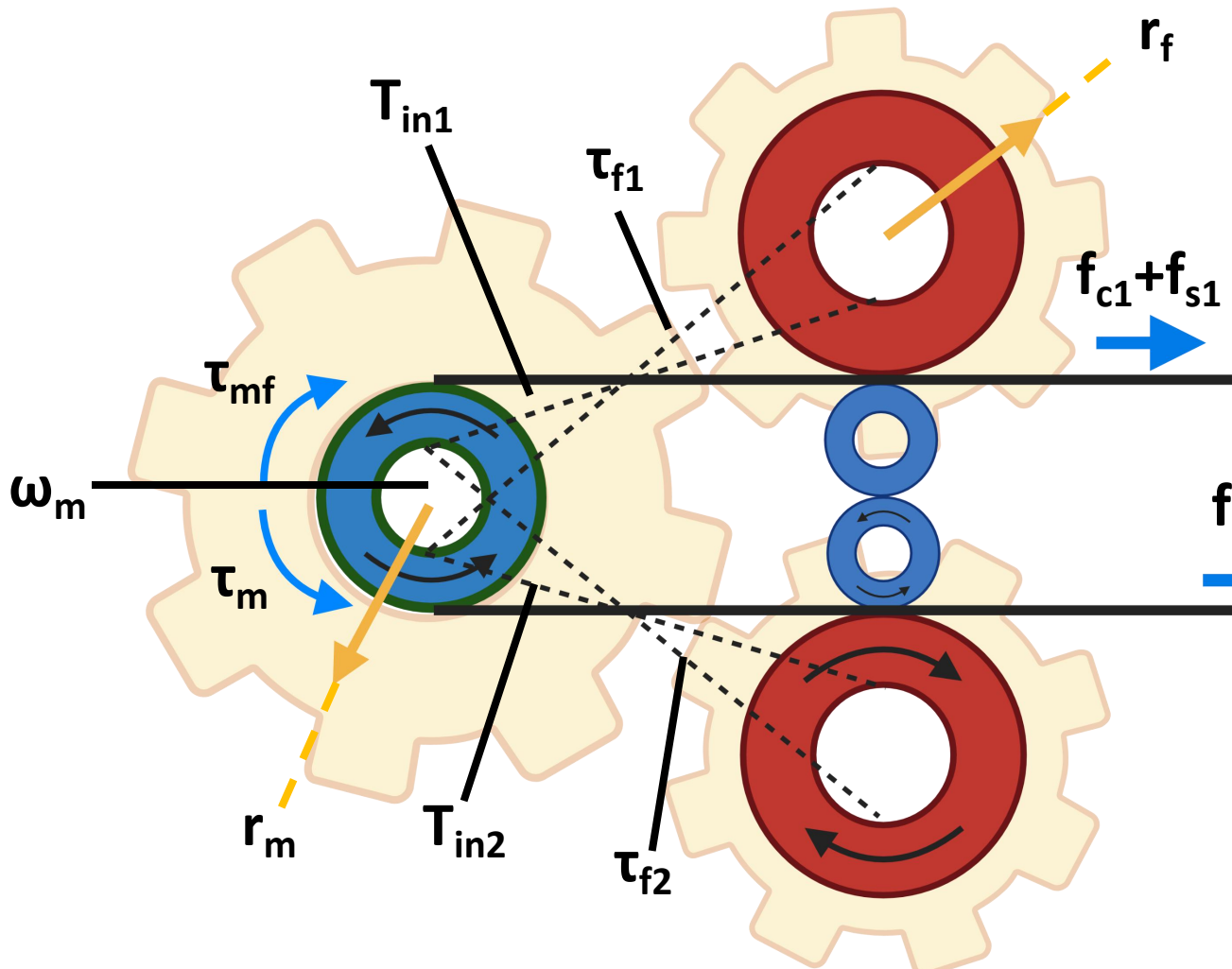
b

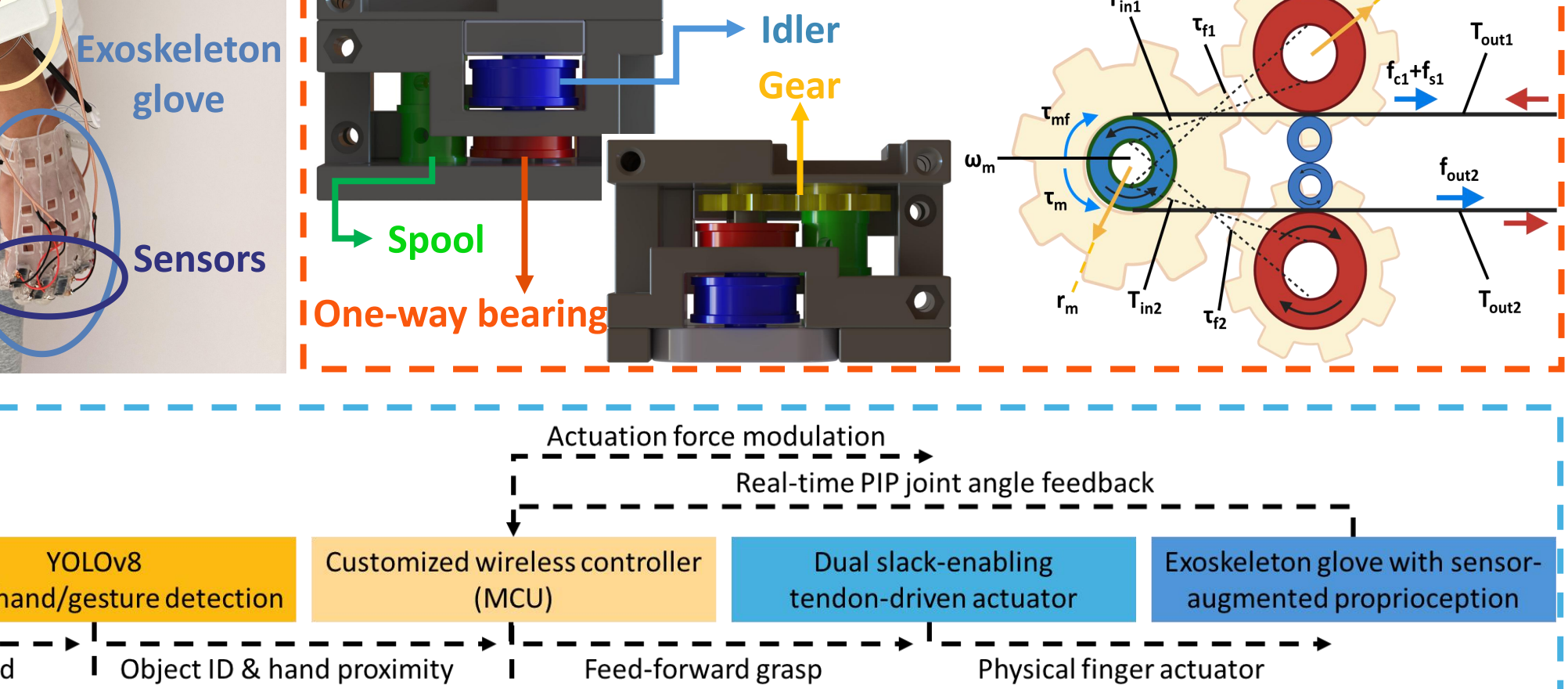

Bat-
Bat+
M2B
M2A
M1B
M1A
Motors

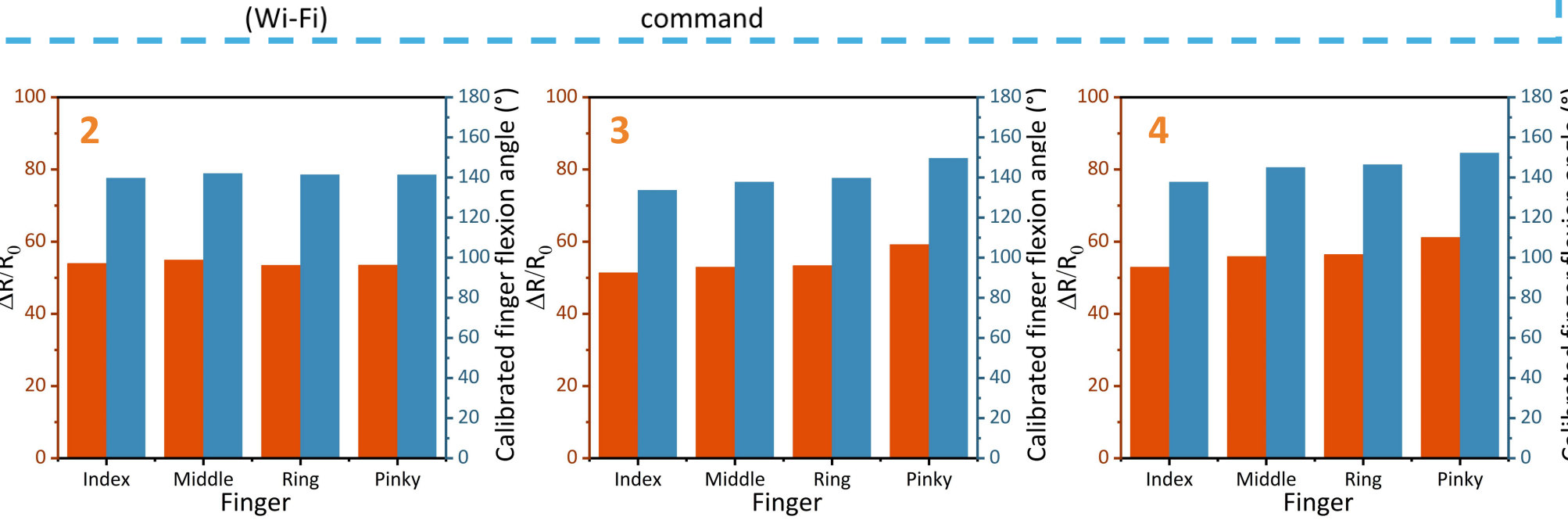
c

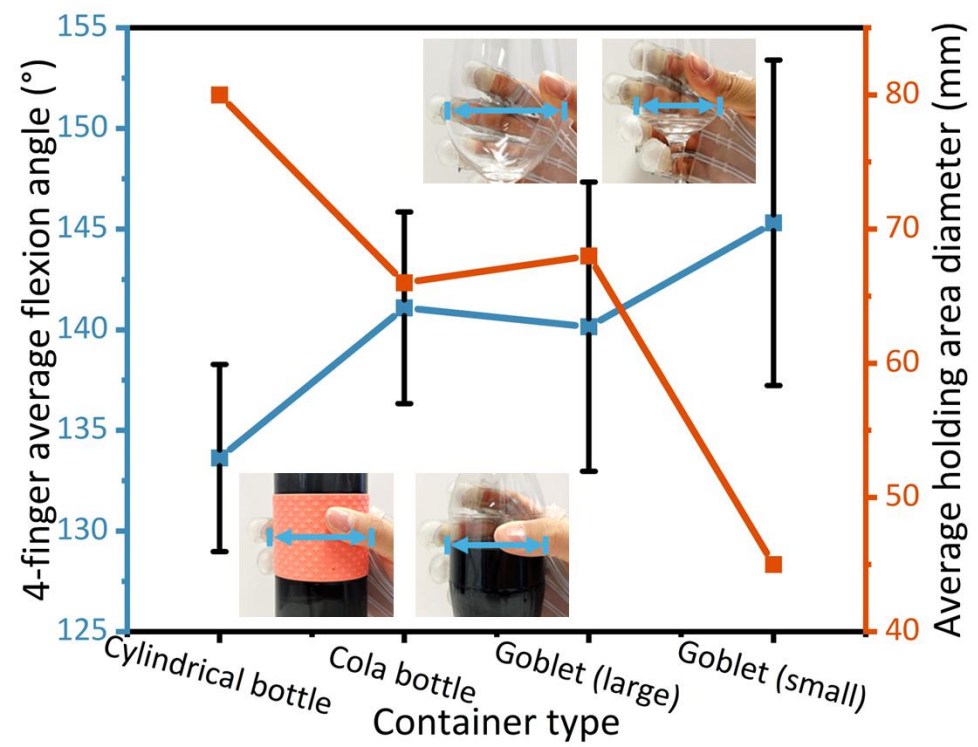

U4
TP4056X
TEMP
CE
PROG
VCC
BAT
STDBY
CHRG
EP
GND
R12 1K2
R13 1K
R14 1K
C11 100nF
C12 10uF
D3 Green
D4 Red
R8 fuse
C6 10uF
P2
Header 2
Q1
SI2301BDS-T1-E3
R11 100k
U2
Mux_4_in_1
/EN
Y1
Y0
VDD
Y2
GND
Y3
A
Y
B
R1 10k
R2 1k
R5 100k
R6 1M
C3 100nF
C17 100nF
U5
U1
U8
U11
U10
REF3025 SOT23
C16 10uF
C15 10uF
C1 10uF
C2 10uF
C18 10uF
C19 10uF
C23 10uF
C24 10uF
C21 10uF
C22 10uF
C20 100nF
C25 100nF
C14 100nF
MF17CA, CLD-Diode
SMA_edge_conn
J1
J2
J3
J4
J5
R36
R31
R30
R37
R38
P5
Header 4X2
C26 10uF
P1
Header 16
P3
R7 NC
R15 fuse
C13 10uF
R9 fuse NC
R10 NC
^^ USB plug here
U3
AP2114H-3.3TRG1
C8 10uF
C9 100nF
C5 10uF
C7 100nF
L1 Inductor 10mH
C4 10uF

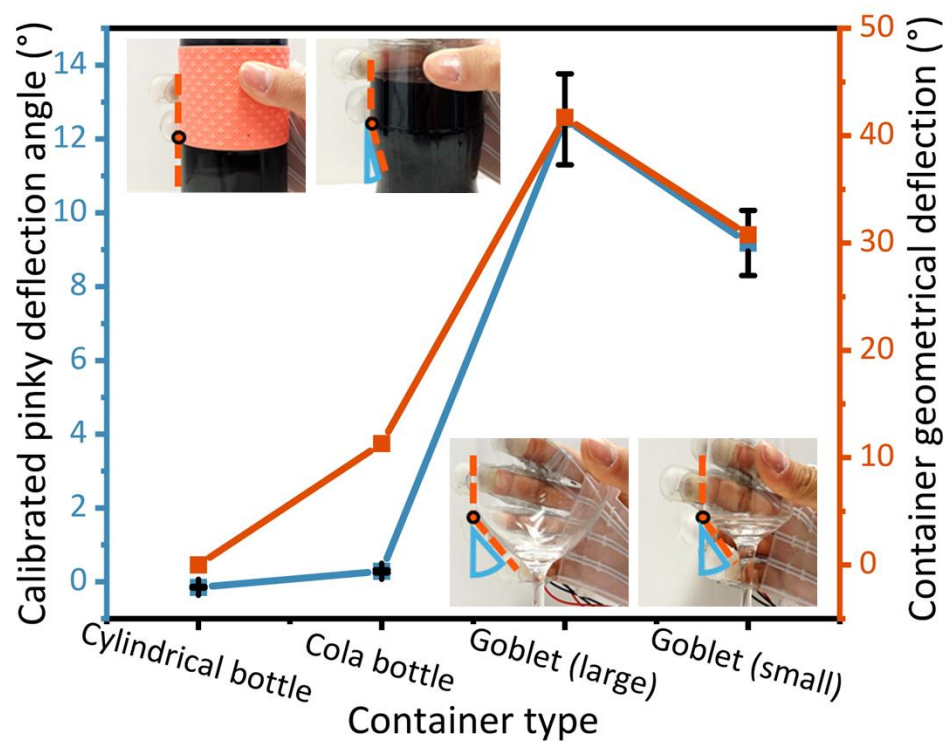

r_f
T_{out1}
$f_{c1}+f_{s1}$
f_{c2}
T_{out2}

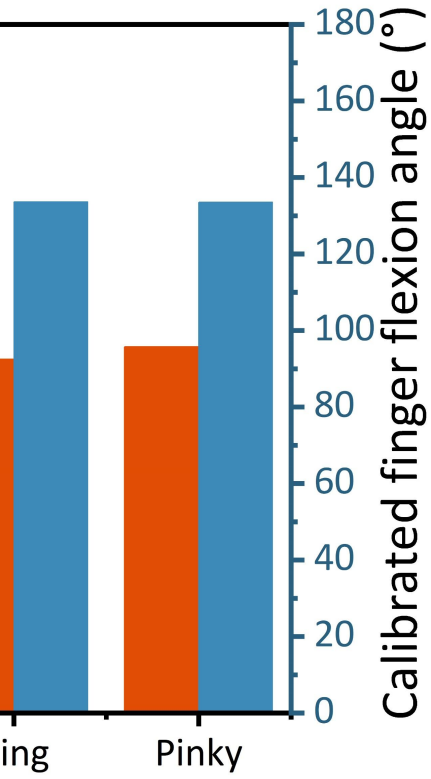

r_f
T_{in1}
τ_{f1}
$f_{c1}+f_{s1}$
τ_{mf}
ω_m
τ_m
r_m
T_{in2}
τ_{f2}


Exoskeleton glove
Sensors
Idler
Gear
Spool
One-way bearing
Actuation force modulation
Real-time PIP joint angle feedback
YOLOv8 hand/gesture detection
Customized wireless controller (MCU)
Dual slack-enabling tendon-driven actuator
Exoskeleton glove with sensor-augmented proprioception
Object ID & hand proximity signal (Wi-Fi)
Feed-forward grasp command
Physical finger actuator
Release command signal (Wi-Fi)
Release/open-hand command

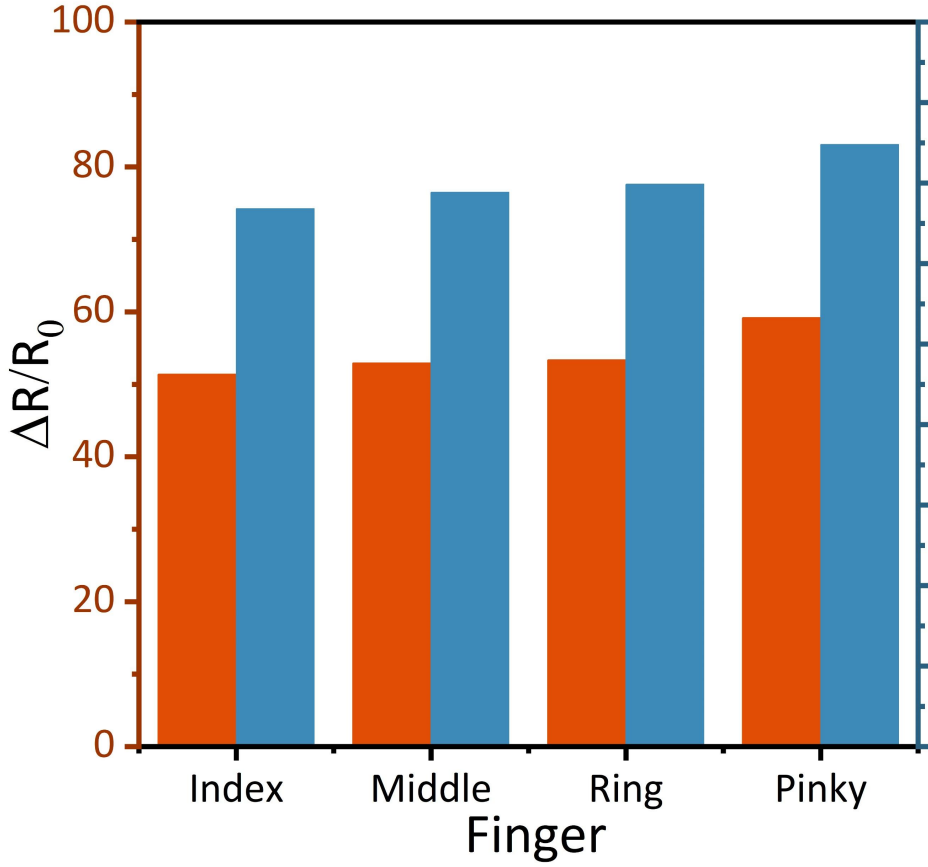

2
3
4
ΔR/R0
Calibrated finger flexion angle (°)
Index
Middle
Ring
Pinky
Finger

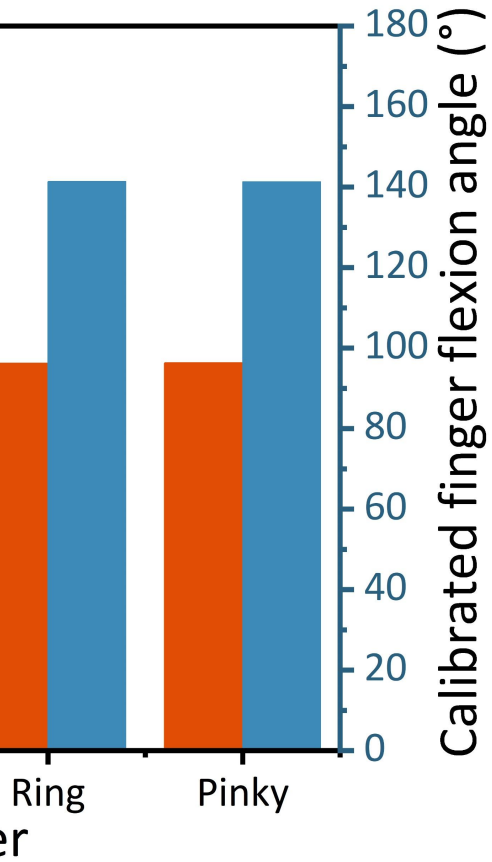

4-finger average flexion angle (°)
Average holding area diameter (mm)
Cylindrical bottle
Cola bottle
Goblet (large)
Goblet (small)
Container type


Calibrated pinky deflection angle (°)
Container geometrical deflection (°)
Cylindrical bottle
Cola bottle
Goblet (large)
Goblet (small)
Container type

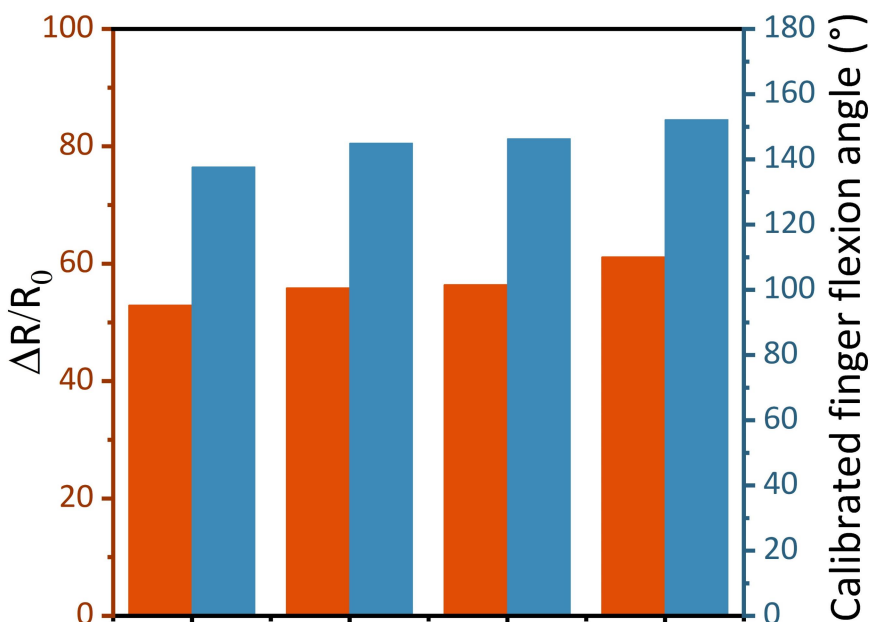

180
160
140
120
100
80
60
40
20
0
Calibrated finger flexion angle (°)
ing
Pinky

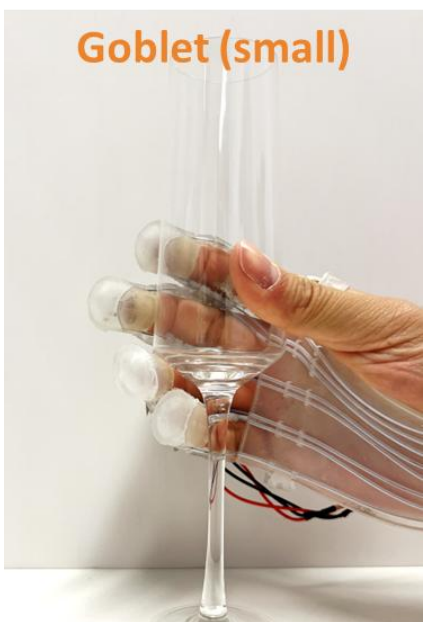
Cylindrical bottle

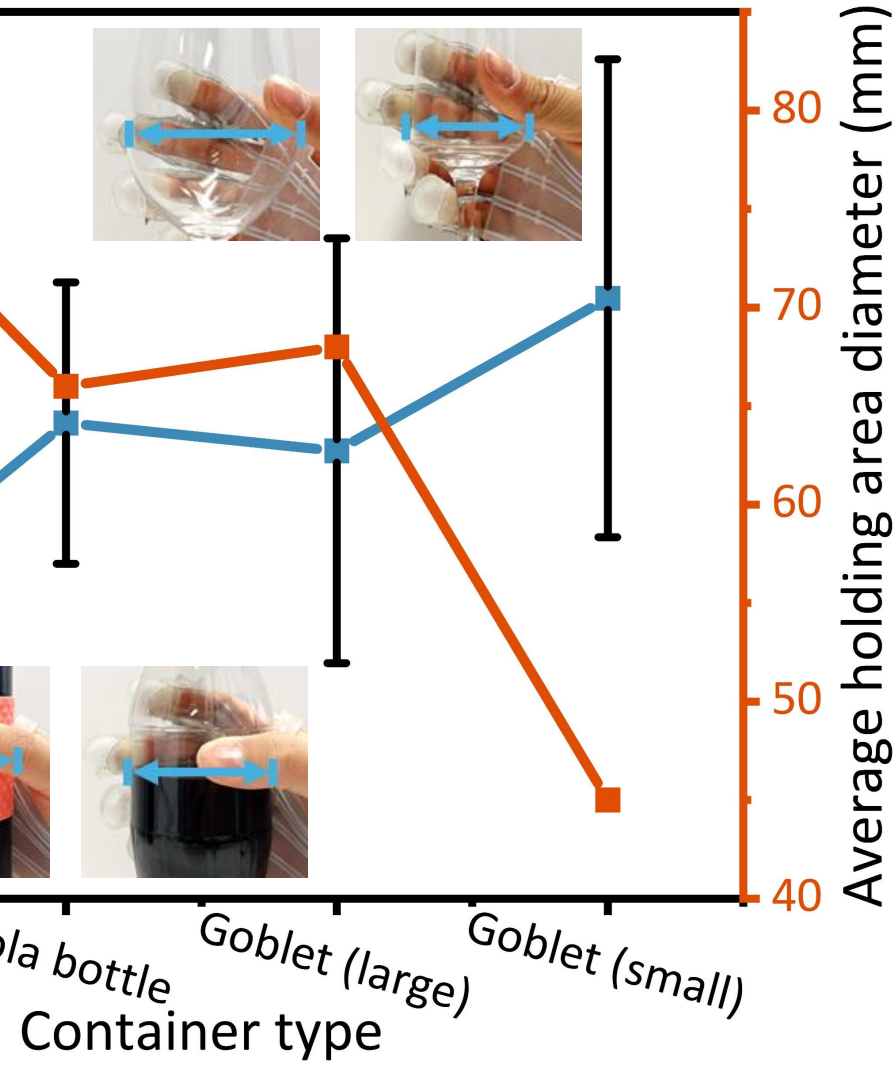

100
80
60
40
20
0
ΔR/R0
Index
Middle
Ring
Pinky
Finger

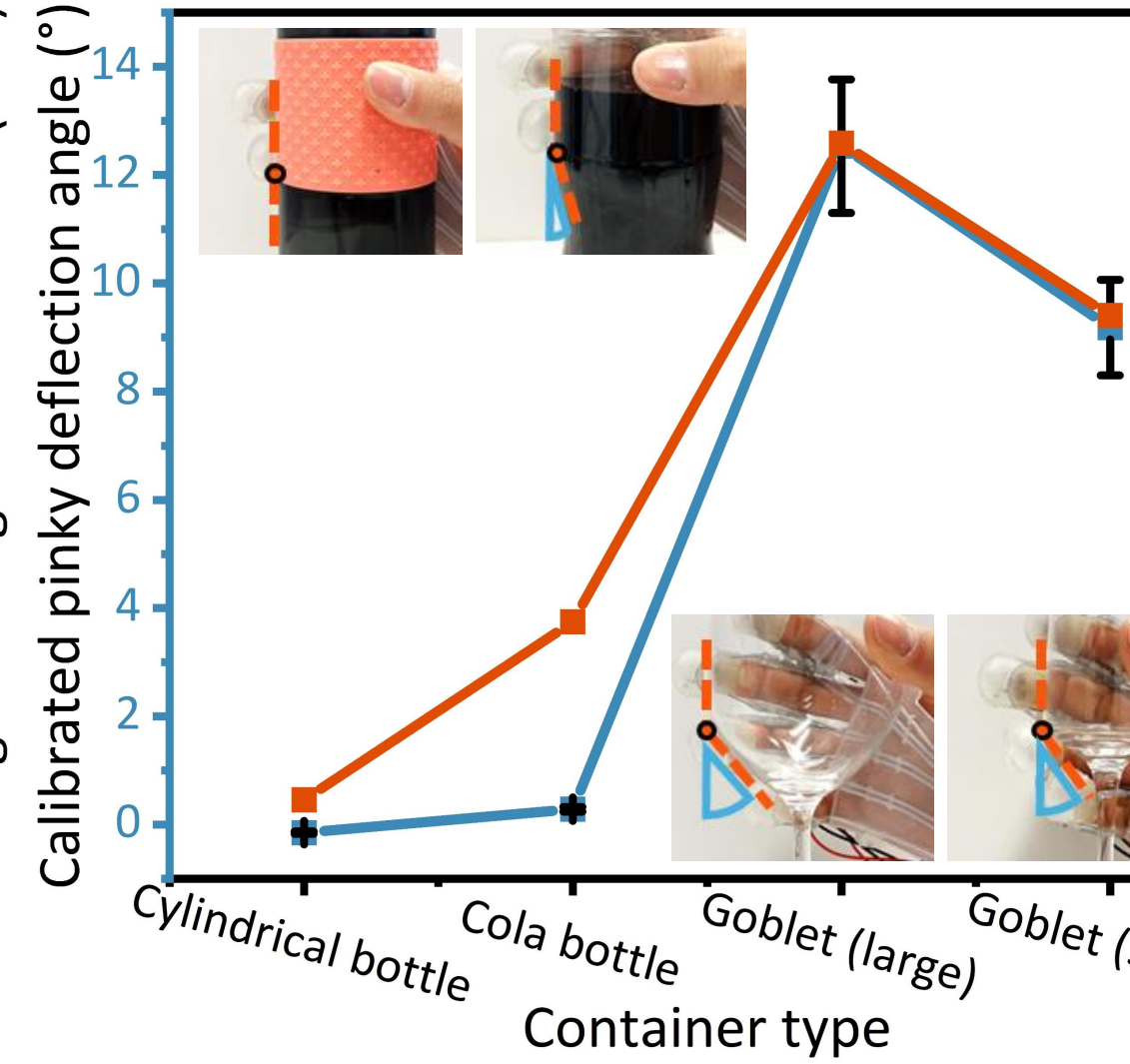

180
160
140
120
100
80
60
40
20
0
Calibrated finger flexion angle (°)
Ring
Pinky
er

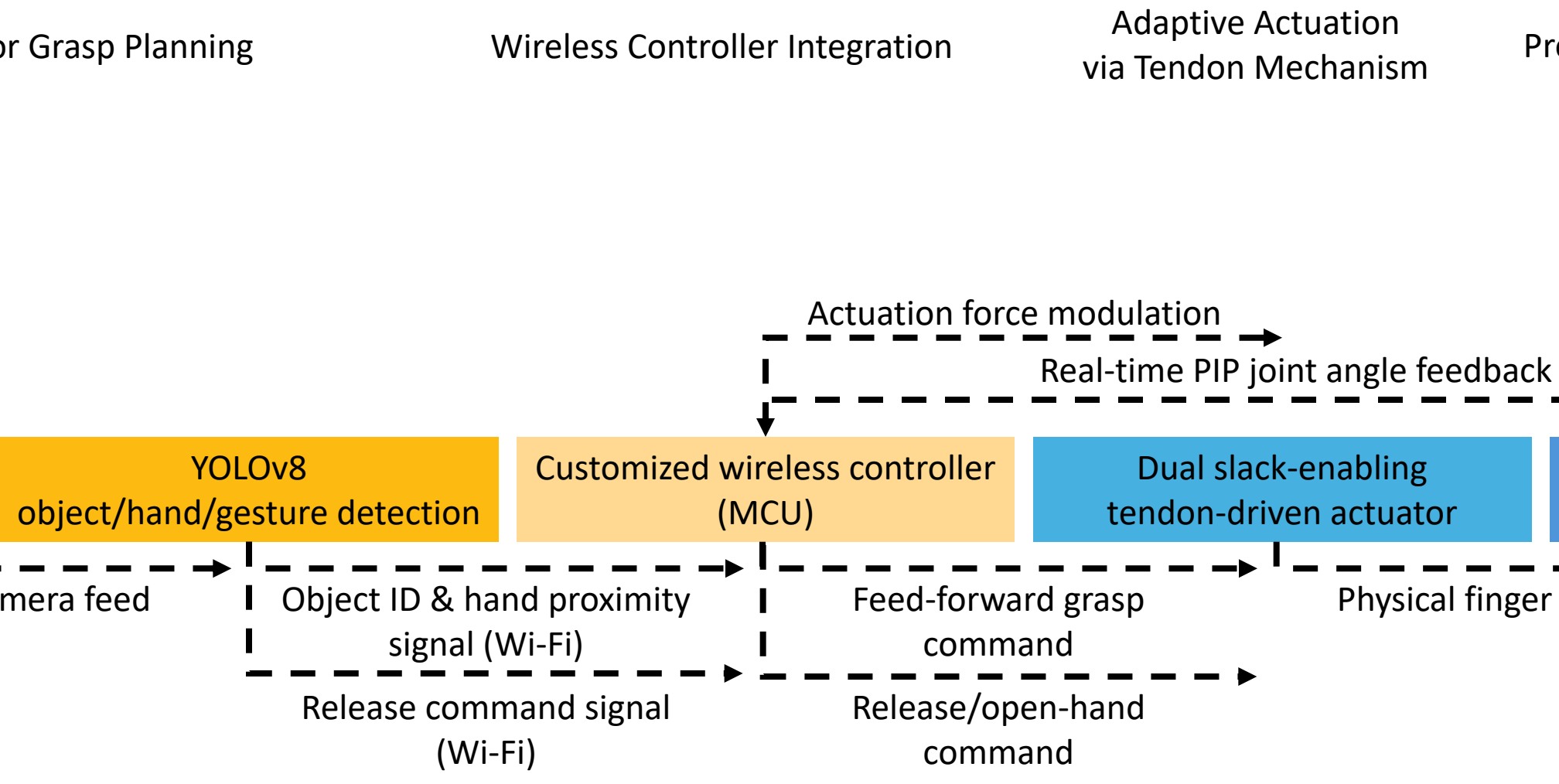
Cola bottle (500mL)


100
80
60
40
20
0
ΔR/R0
180
160
140
120
100
80
60
40
20
0
Calibrated finger flexion angle (°)


Goblet (small)

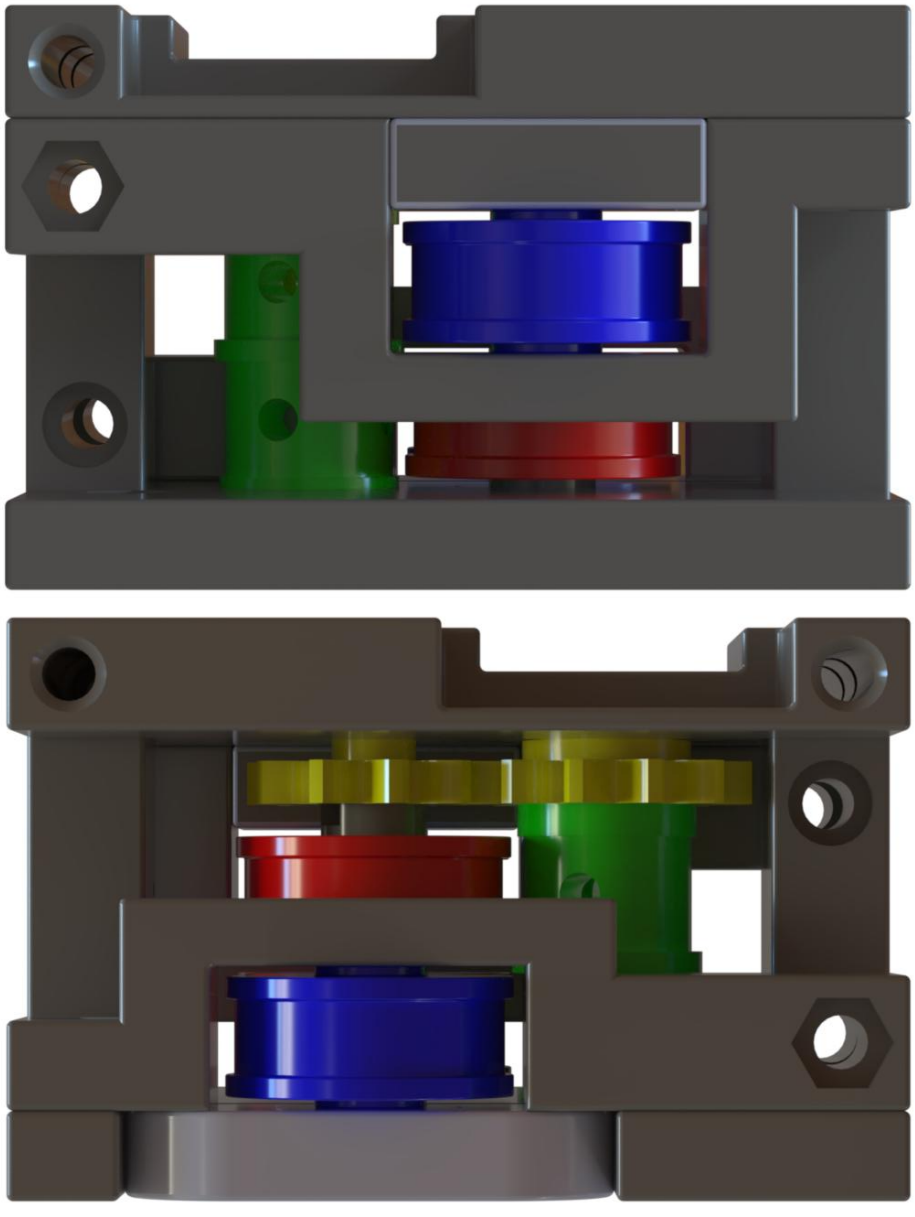

80
70
60
50
40
Average holding area diameter (mm)
la bottle
Goblet (large)
Goblet (small)
Container type


14
12
10
8
6
4
2
0
Calibrated pinky deflection angle (°)
Cylindrical bottle
Cola bottle
Goblet (large)
Container type

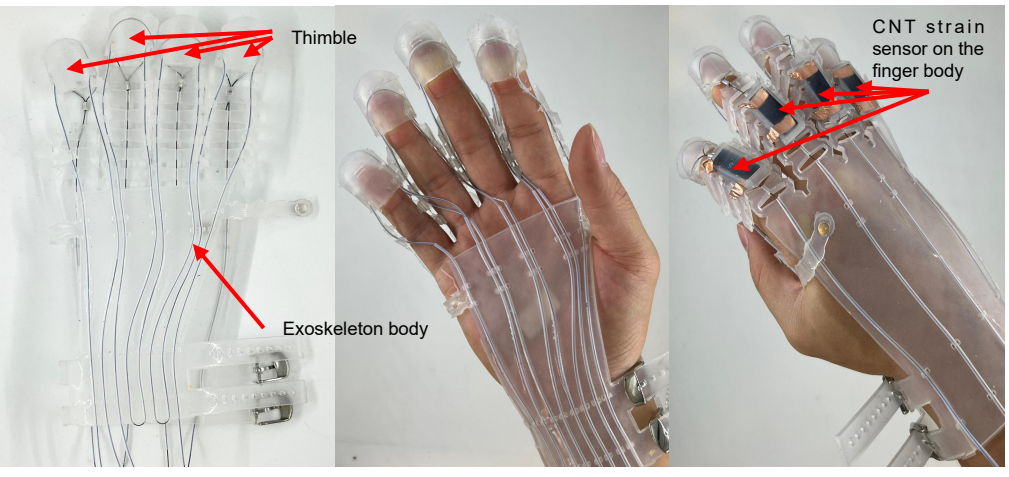

or Grasp Planning
Wireless Controller Integration
Adaptive Actuation
via Tendon Mechanism
Pr
Actuation force modulation
Real-time PIP joint angle feedback
YOLOv8
object/hand/gesture detection
Customized wireless controller
(MCU)
Dual slack-enabling
tendon-driven actuator
mera feed
Object ID & hand proximity
signal (Wi-Fi)
Feed-forward grasp
command
Physical finger
Release command signal
(Wi-Fi)
Release/open-hand
command

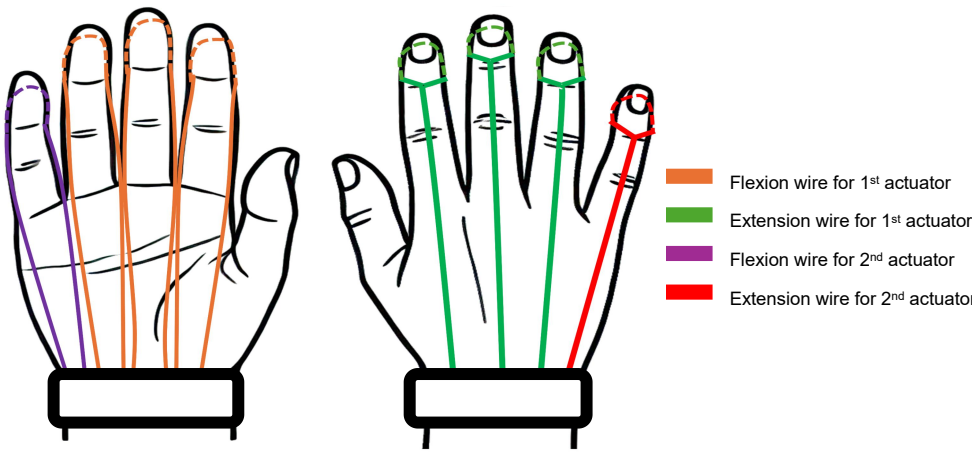
Side

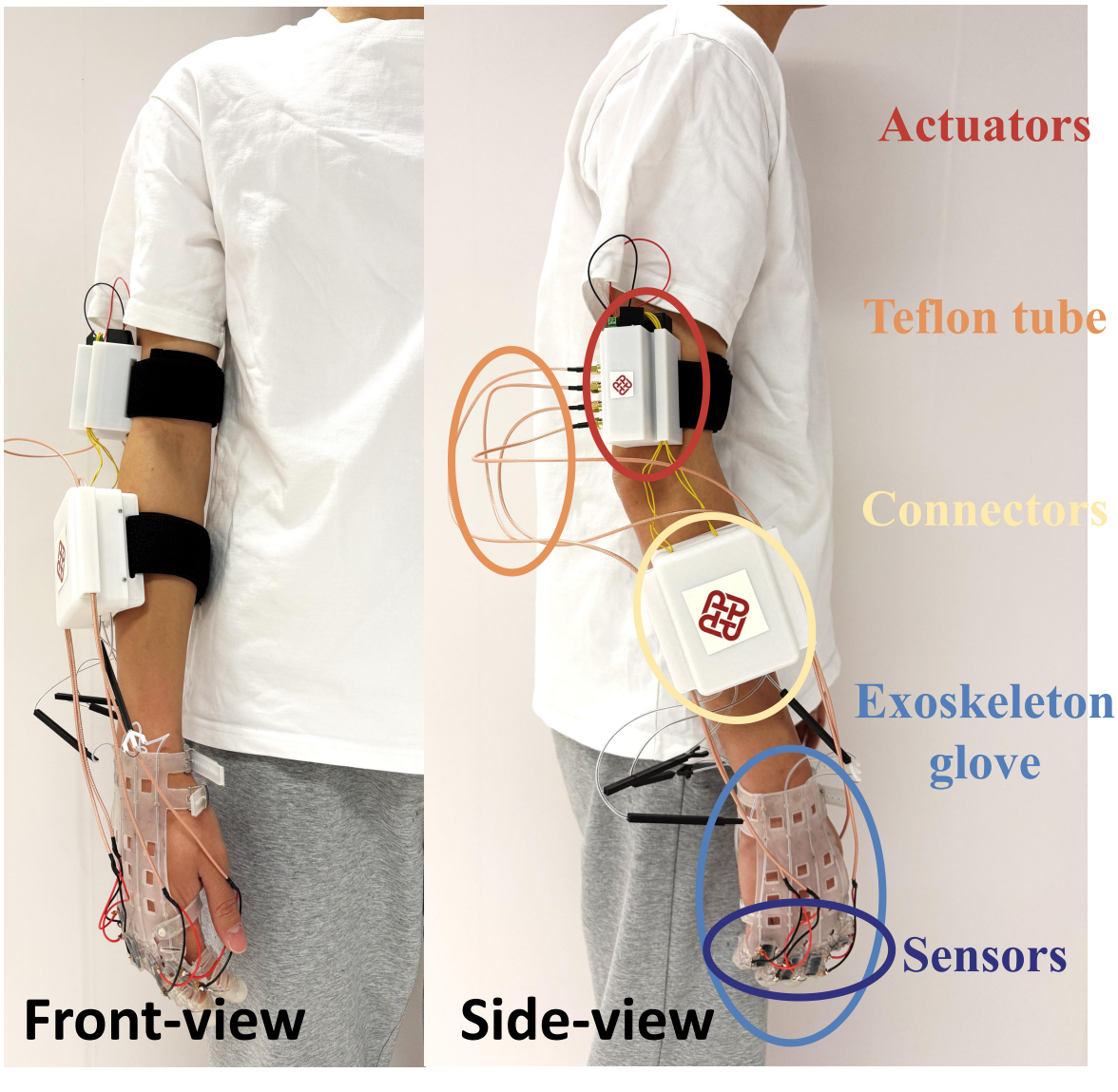
Front

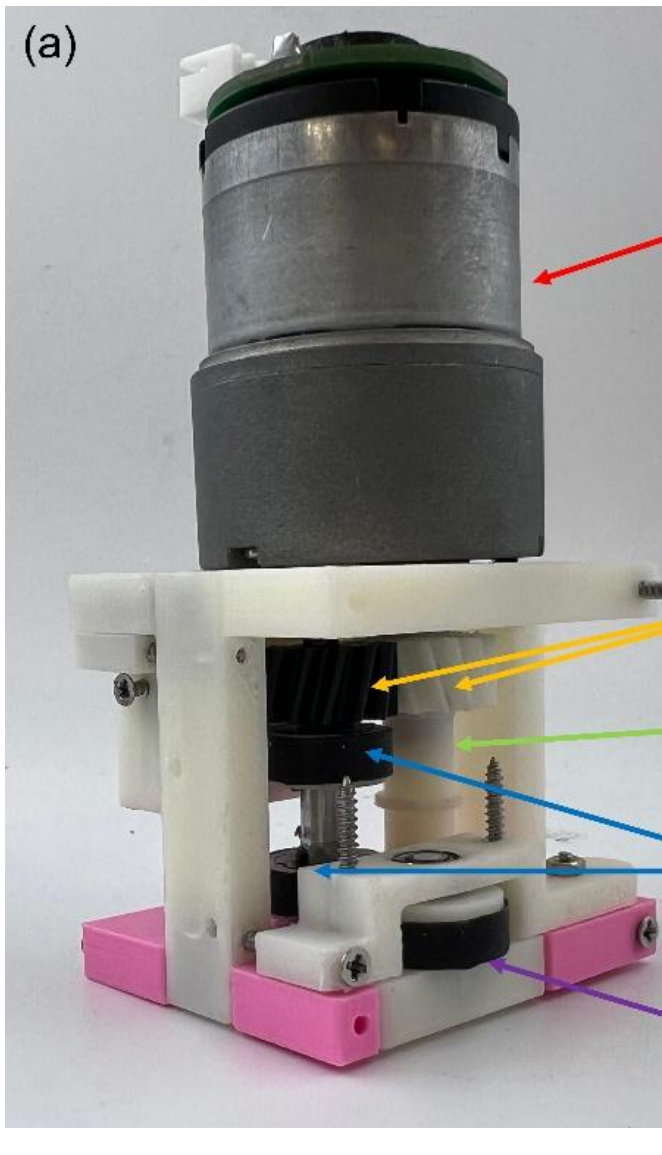


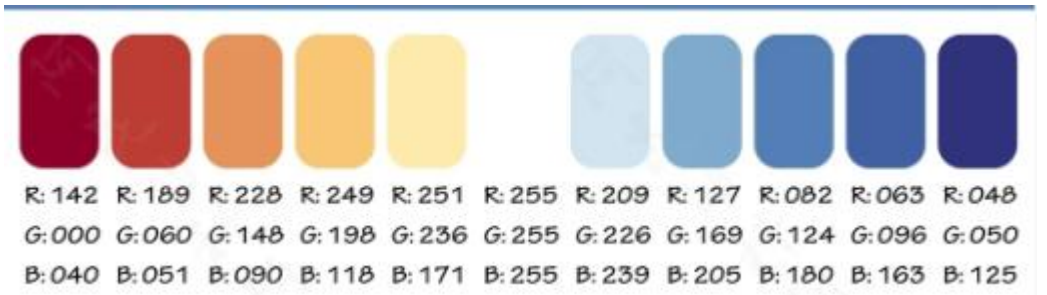
Gear | Spool | One-way bearing | Idler

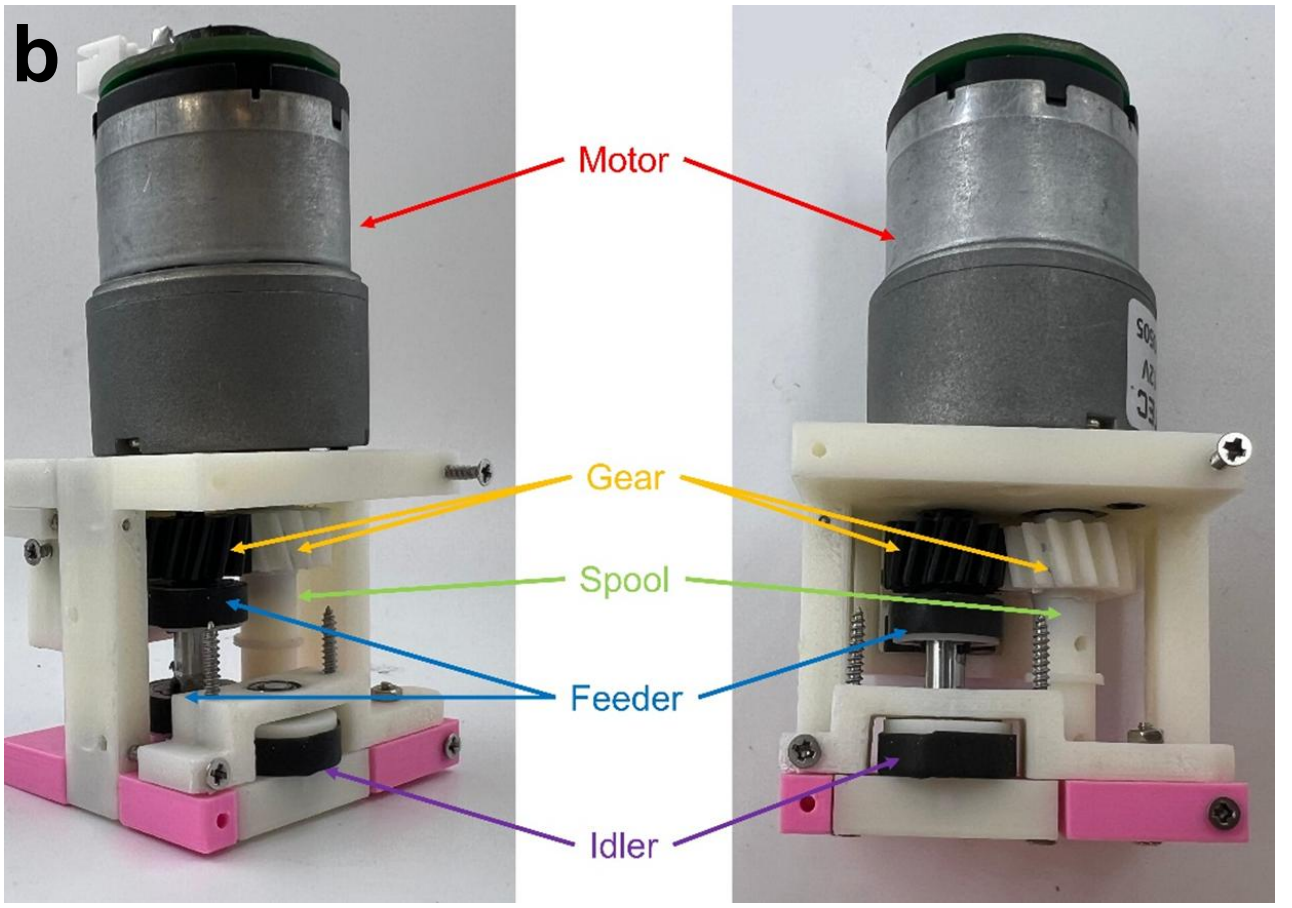

Thimble
Exoskeleton body
CNT strain sensor on the finger body

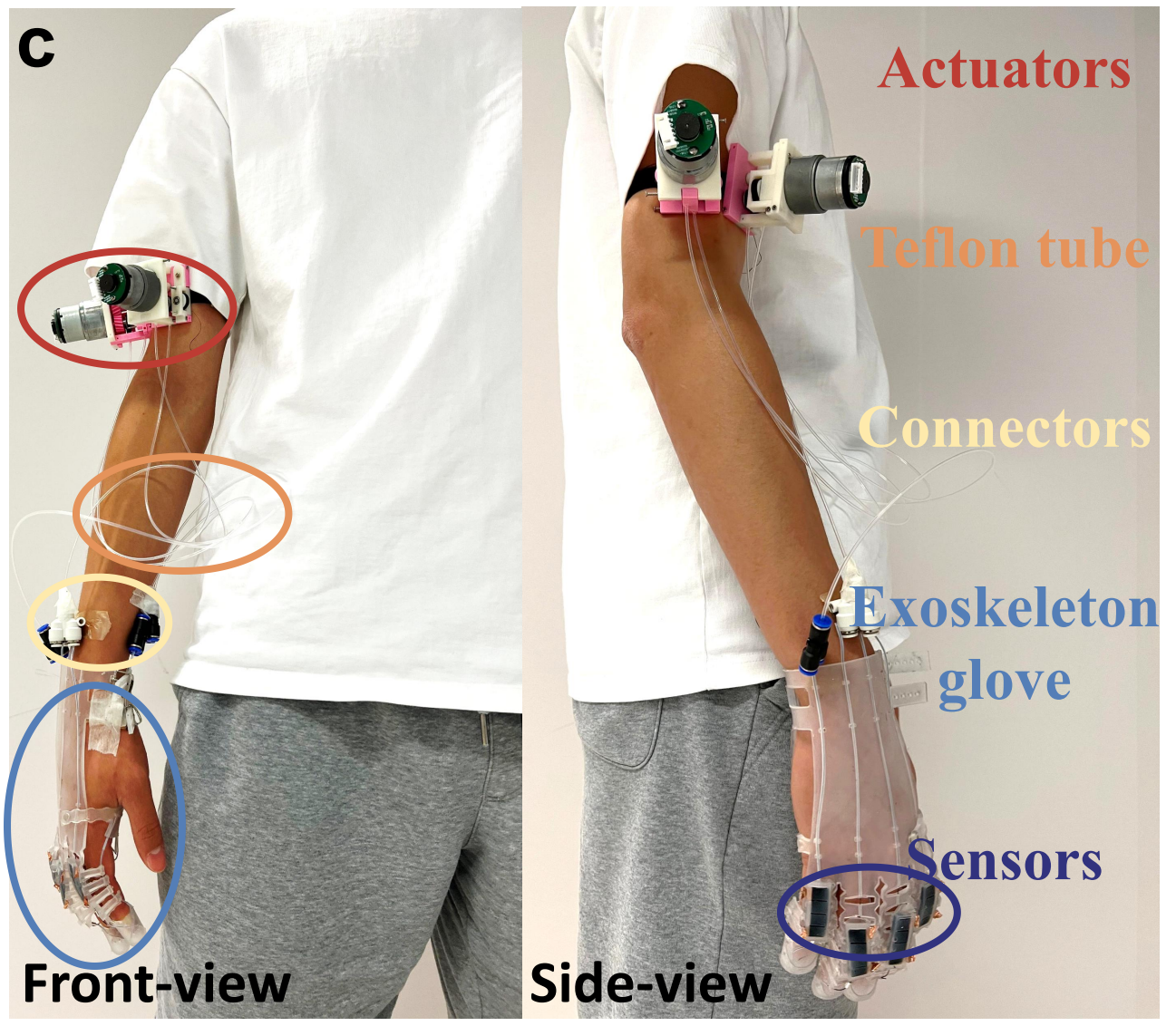

Flexion wire for 1st actuator
Extension wire for 1st actuator
Flexion wire for 2nd actuator
Extension wire for 2nd actuator

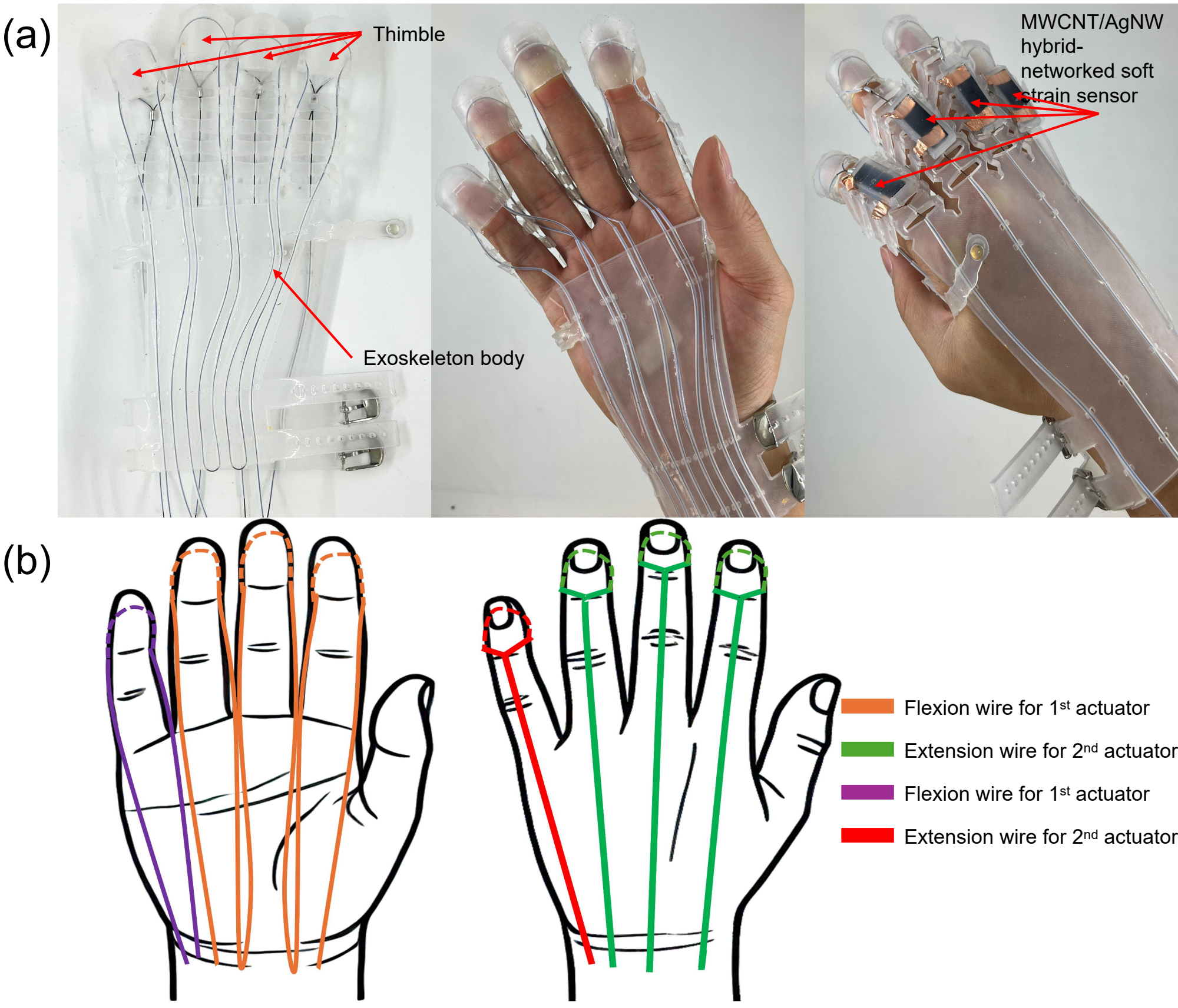

Front-view
Side-view
Actuators
Teflon tube
Connectors
Exoskeleton glove
Sensors

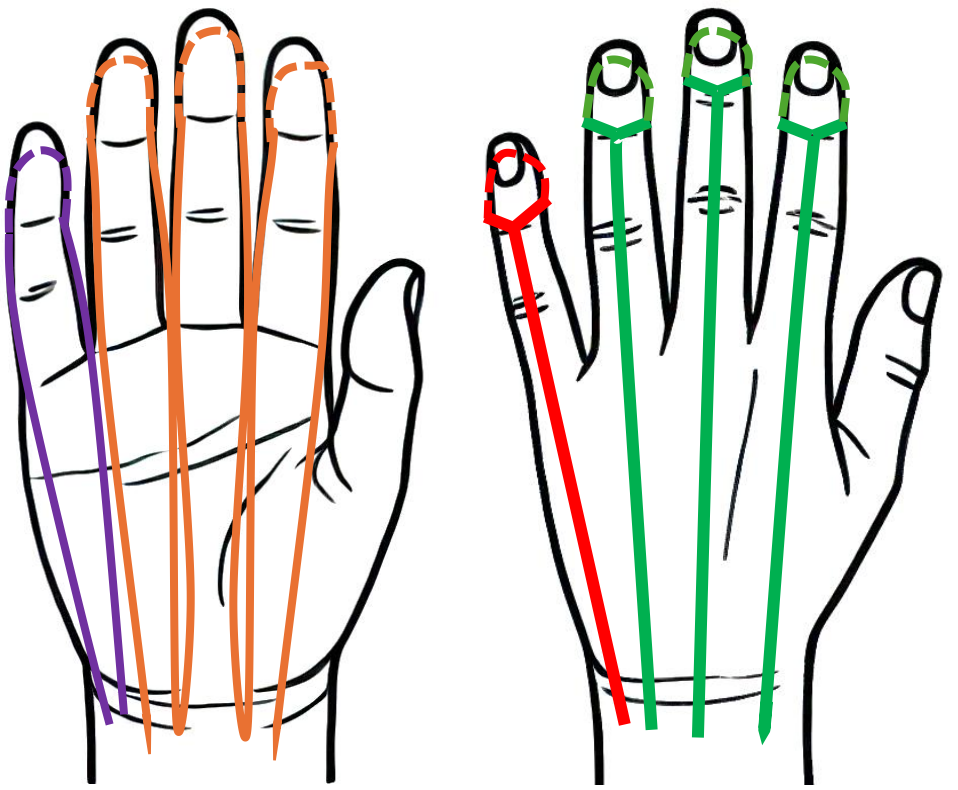

(a)

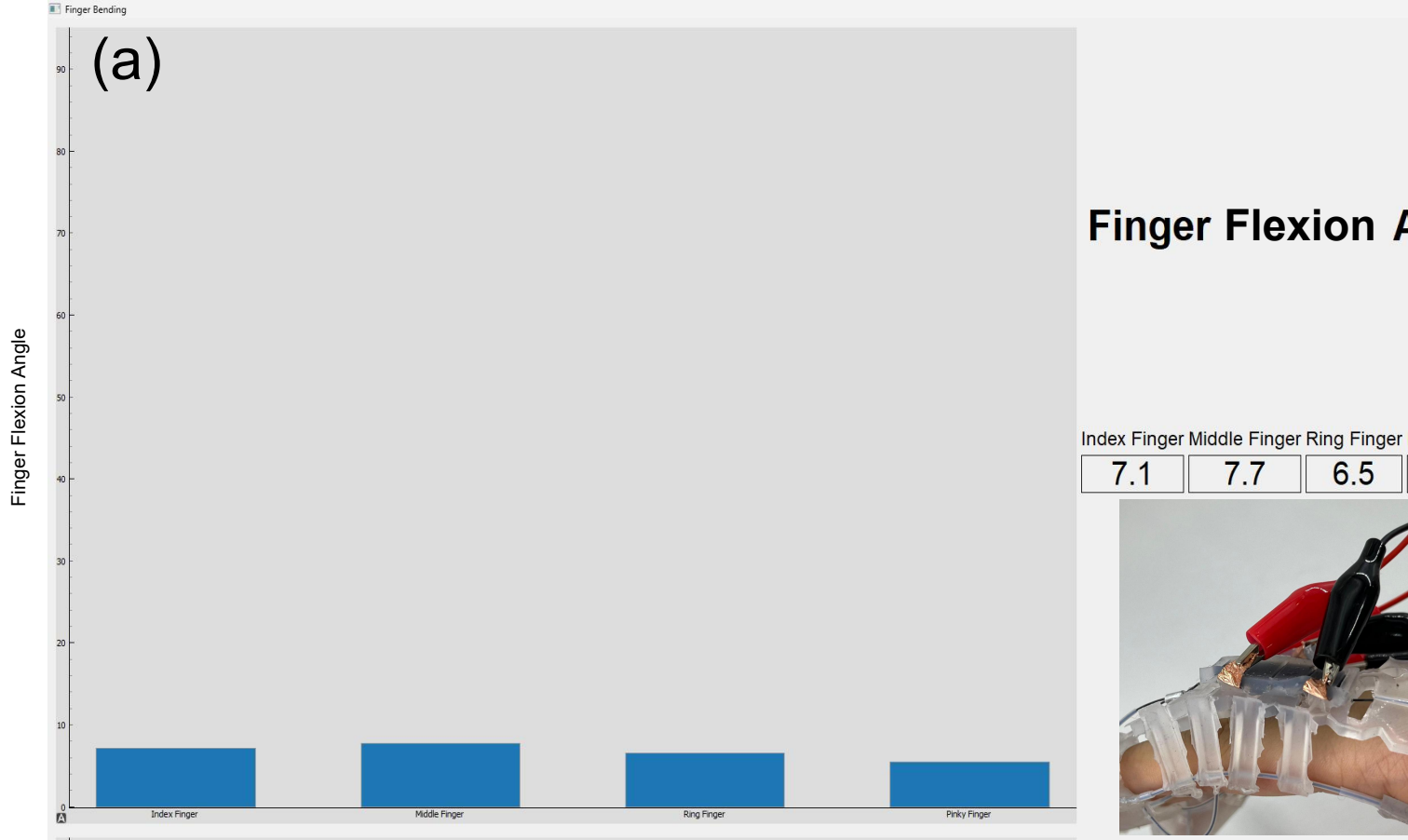

R: 142 R: 189 R: 228 R: 249 R: 251 R: 255 R: 209 R: 127 R: 082 R: 063 R: 048
G: 000 G: 060 G: 148 G: 198 G: 236 G: 255 G: 226 G: 169 G: 124 G: 096 G: 050
B: 040 B: 051 B: 090 B: 118 B: 171 B: 255 B: 239 B: 205 B: 180 B: 163 B: 125

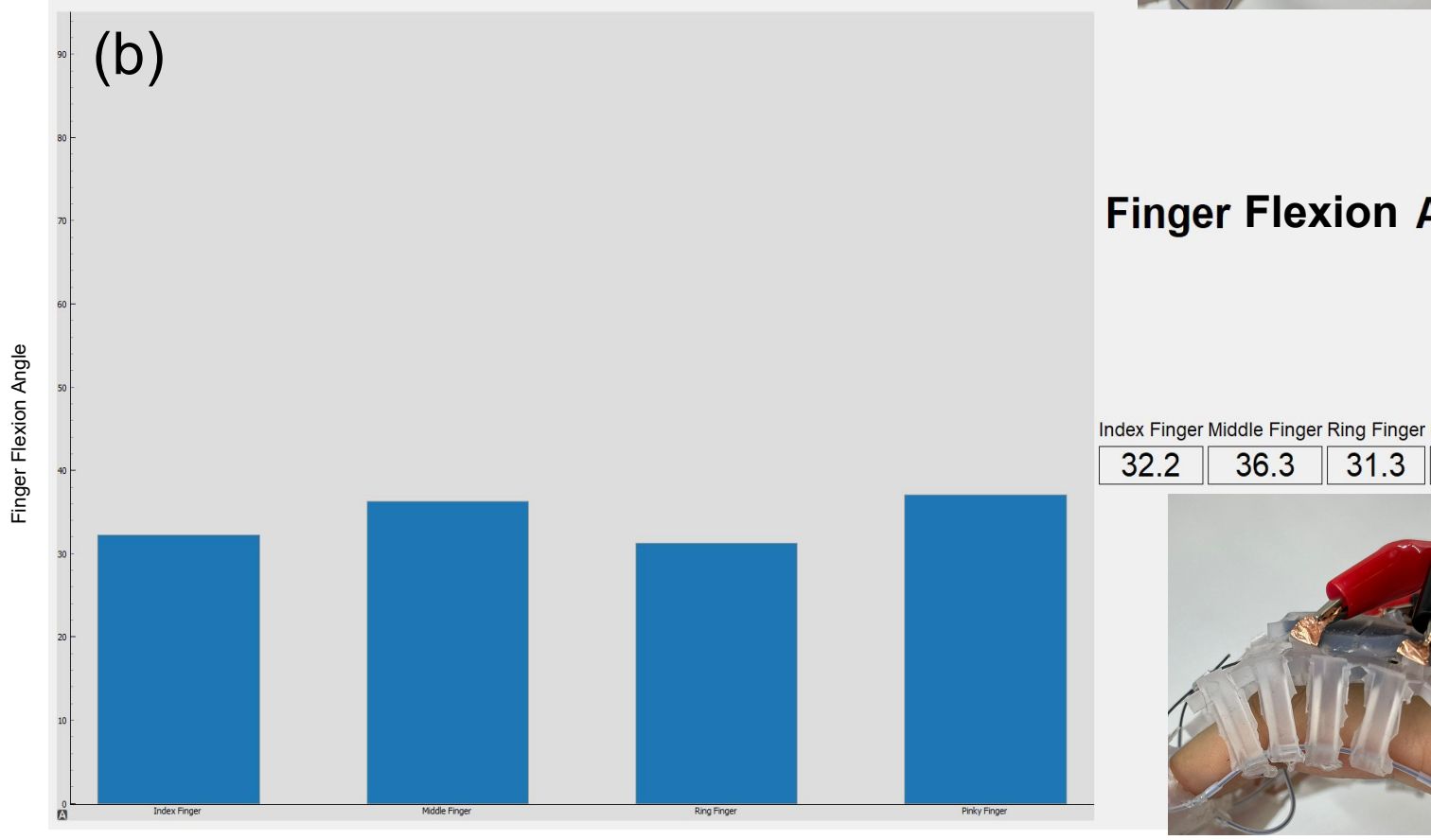

b
Motor
Gear
Spool
Feeder
Idler

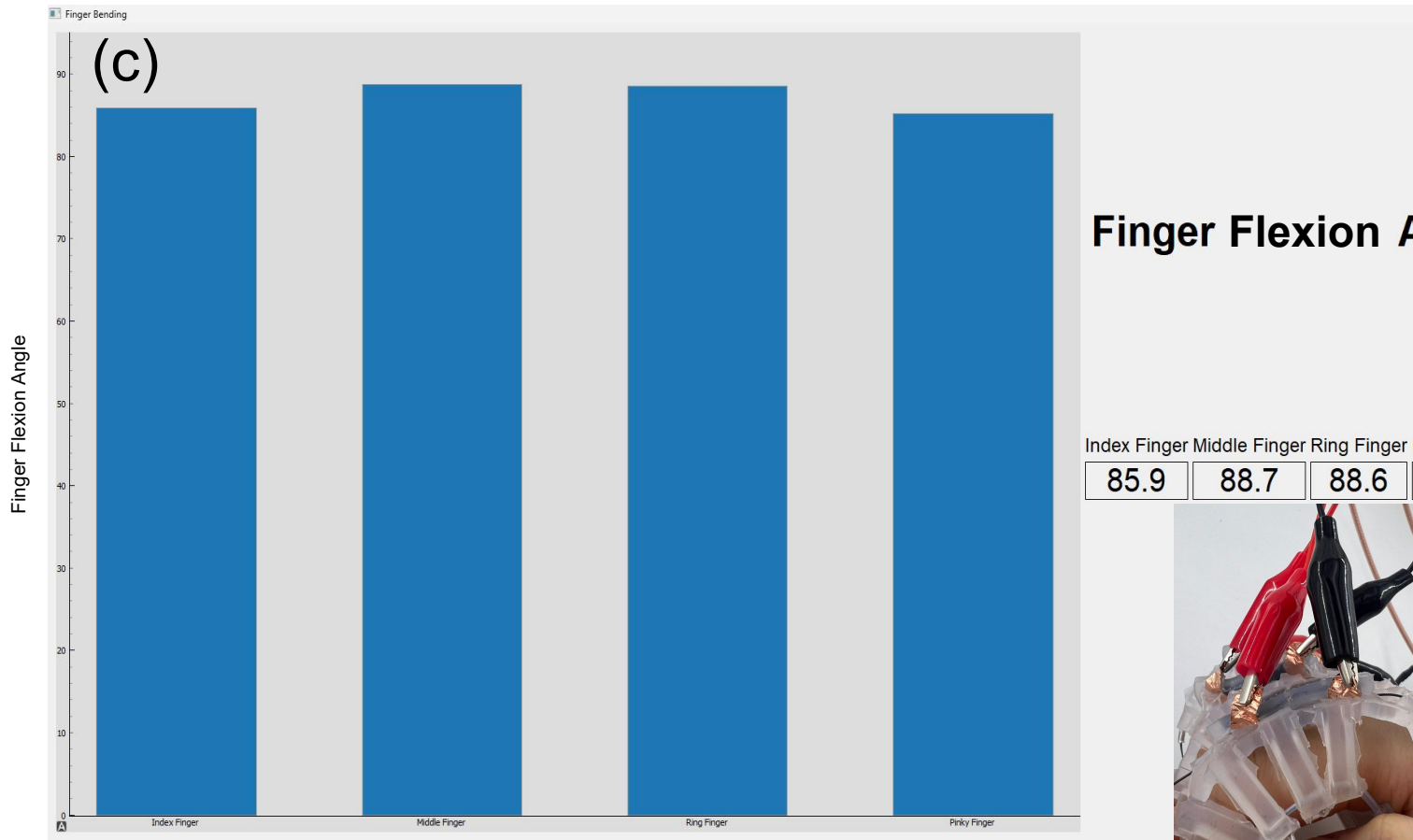

c
Actuators
Teflon tube
Connectors
Exoskeleton glove
Sensors
Front-view
Side-view


(a)
Thimble
Exoskeleton body
MWCNT/AgNW hybrid-networked soft strain sensor
(b)
Flexion wire for 1st actuator
Extension wire for 2nd actuator
Flexion wire for 1st actuator
Extension wire for 2nd actuator




Finger Bending
(a)
Finger Flexion Angle
Index Finger
Middle Finger
Ring Finger
Pinky Finger
Finger Flexion A
Index Finger Middle Finger Ring Finger
7.1
7.7
6.5


(b)
Finger Flexion Angle
Index Finger
Middle Finger
Ring Finger
Pinky Finger
Finger Flexion A
Index Finger Middle Finger Ring Finger
32.2
36.3
31.3


Finger Bending
(c)
Finger Flexion Angle
Index Finger
Middle Finger
Ring Finger
Pinky Finger
Finger Flexion A
Index Finger Middle Finger Ring Finger
85.9
88.7
88.6