Novel Functional Materials

--Carbon Microcoils/（CMC）--

Properties and Potential Application

Dr. Seiji Motojima

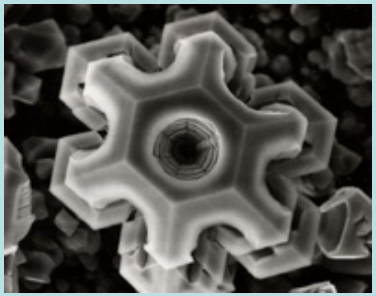
Fellow

Toyota Physical & Chemical Research Institute

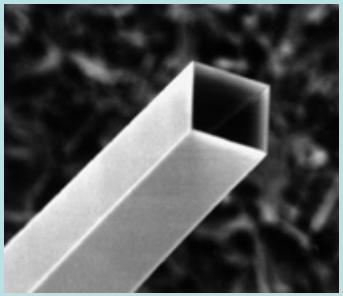
Prologue to selendipitic discovery of silicon nitride microcoils and carbon microcoils ----
---Beautiful face of ceramic single crystals obtained from high corrosive atmosphere using CVD process-------

- **Reaction temperature： 800～2500℃**
- **Corrosive atmosphere: HCl, H_2S, etc**
- **Crystal size:** 10~500 μ m

Golden prizes got in the Micrograph Exhibition for Ceramics Crystals (Ceramic Society of Japan)



1981



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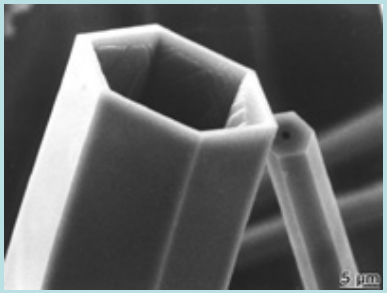

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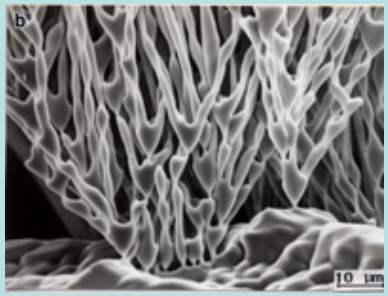

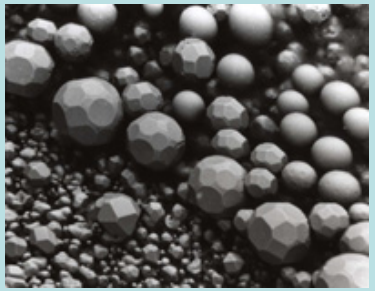

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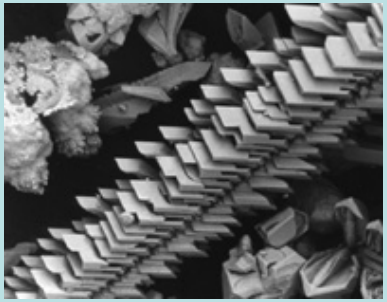

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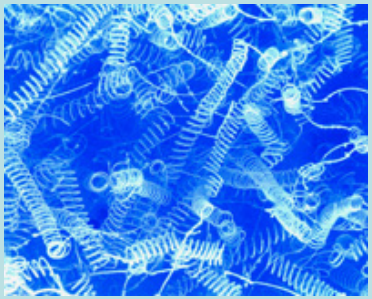

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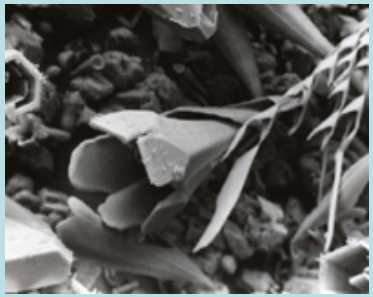
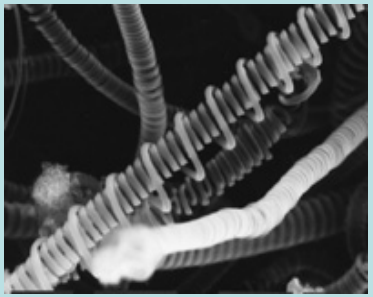


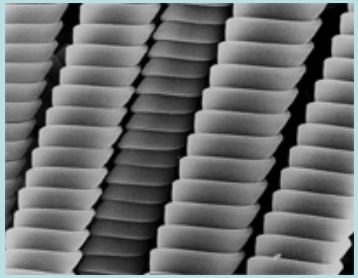
1989

1989



1992

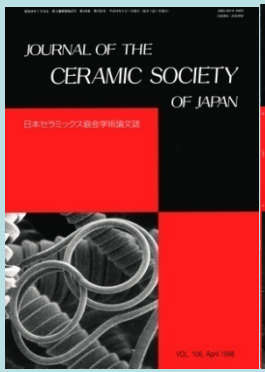
2000

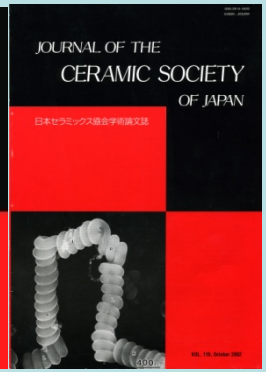


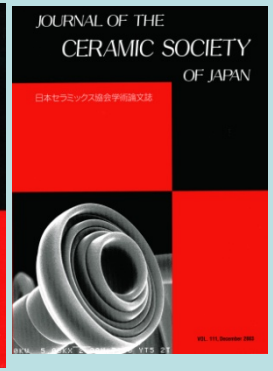
2002

2006

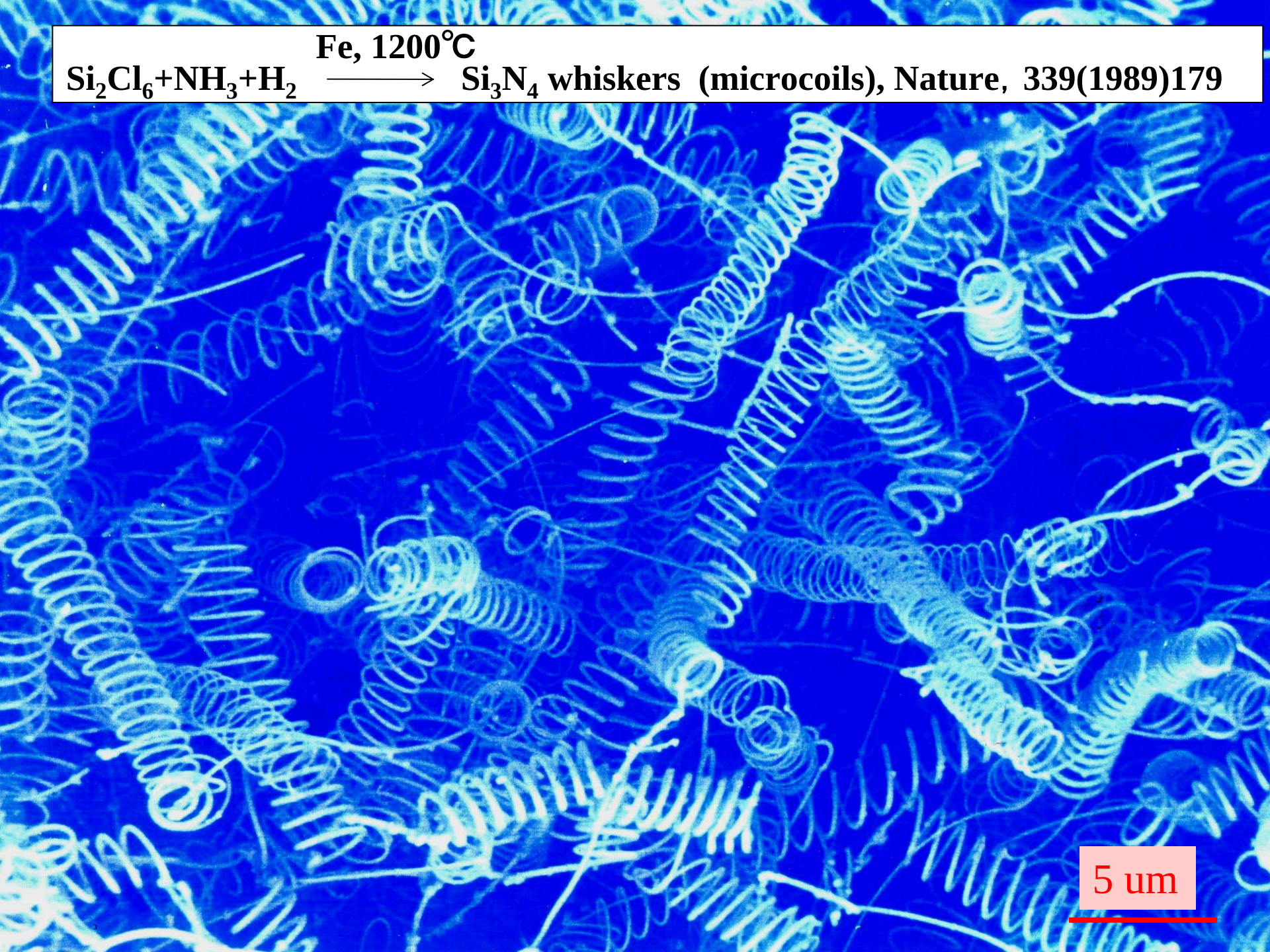
Cover photographs of the Journal of Ceramics







$Si_2Cl_6 + NH_3 + H_2 \xrightarrow{Fe,\ 1200℃} Si_3N_4$ whiskers (microcoils), Nature, 339(1989)179



Carbon Microcoils (Appl. Phys. Lett., 56(1990)321.

What is CMC (Carbon microcoils) ?

1) A kind of vapor grown carbon fiber (VGCF)

2) Preparation process: by metal catalyst-activated CVD

- Carbon source: acetylene (for weld)
- Catalyst: Ni, Fe-Ni, etc.
- Reaction temperature: 750-800℃

3) Morphology:3D-Helical/spiral structure

4) Dimension:
- Coil diameter: ～μm
- Coil Length ～10mm

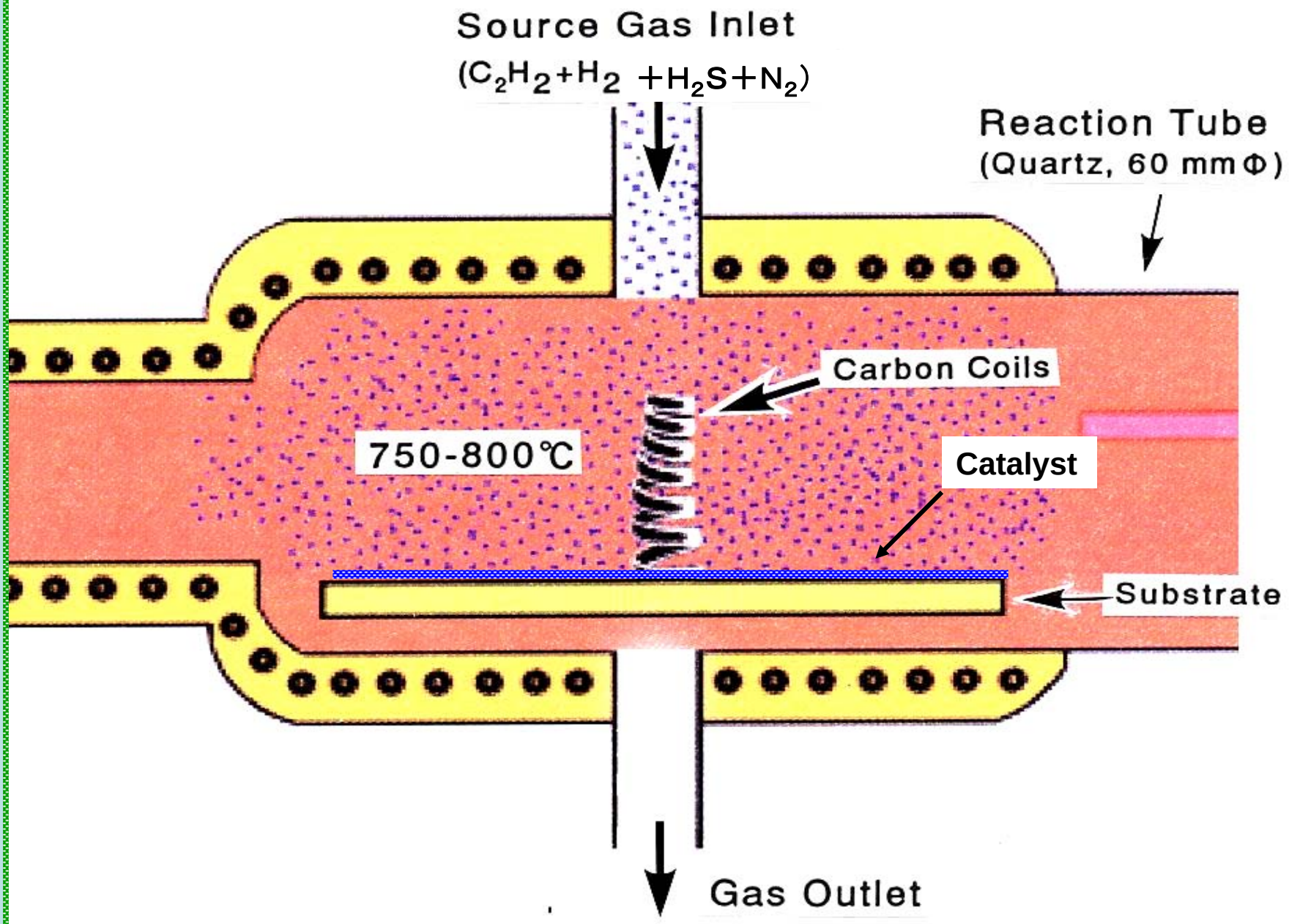
5) Microstructure: Amorphous

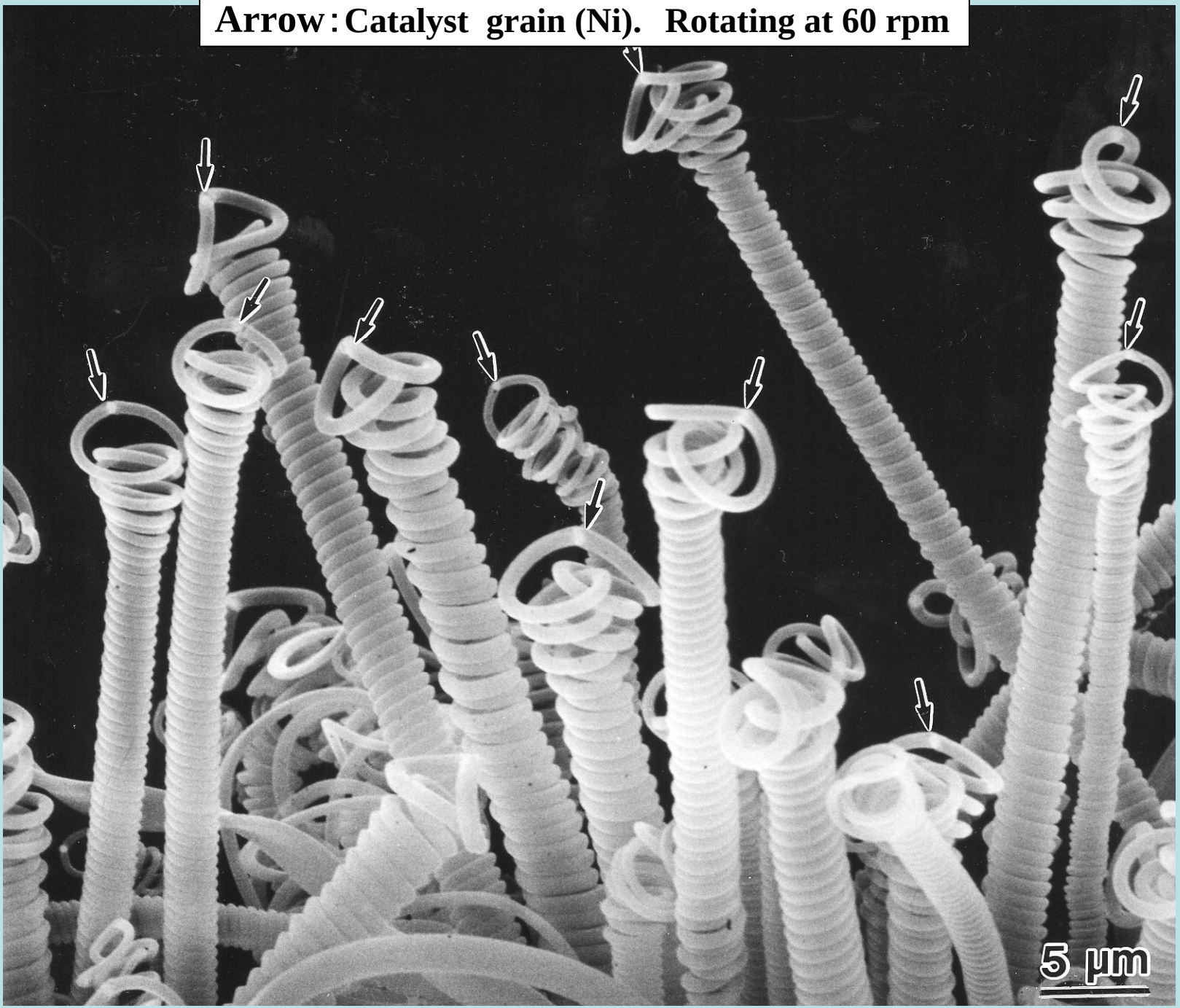
6) Characteristics:
- Coiling-chirality
- High-elasticity
- High interaction with microwaves

Critical difference of CMC from carbon nanotube

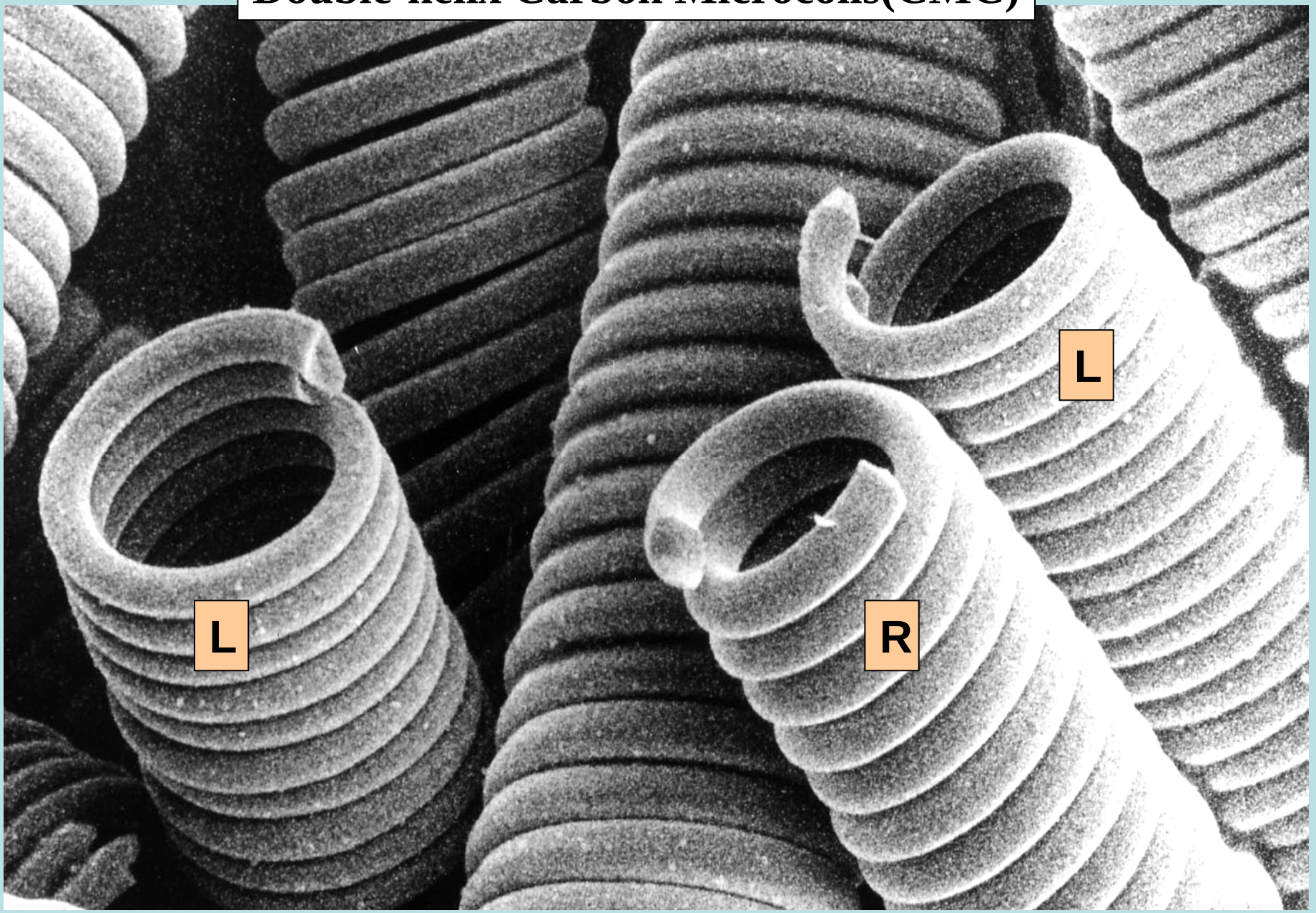
	CMC	CNT
Morphology	3D-helical/spiral	Straight
Dimension	Coil diam: ~μm Fiber diam:0.01~0.5μm	- ~nm
Crystallinity	Amorphous	Crystalline
Pore in the fiber axis	none	Tube-like pore
Interaction with microwave	high	none

Reaction tube for the preparation of carbon microcoils (CMC)



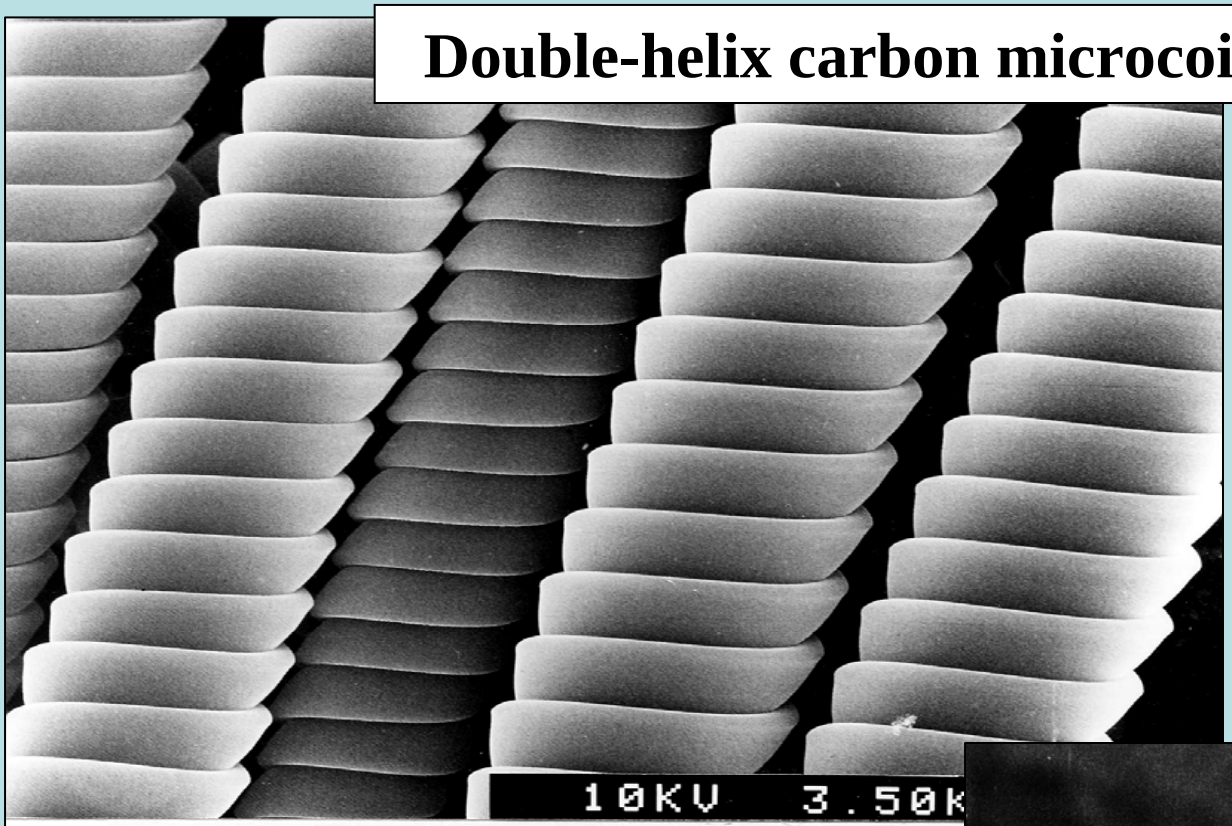

Arrow : Catalyst grain (Ni). Rotating at 60 rpm
5 μm

Double-helix Carbon Microcoils(CMC)

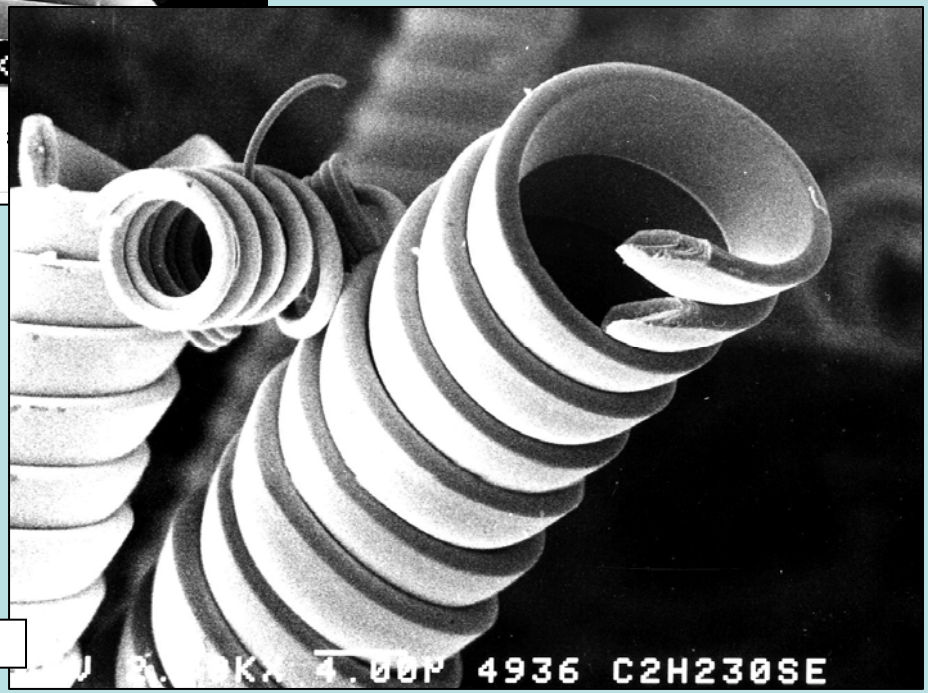


Double-helix carbon microcoil (flat-type)

Commercially available representative CMC

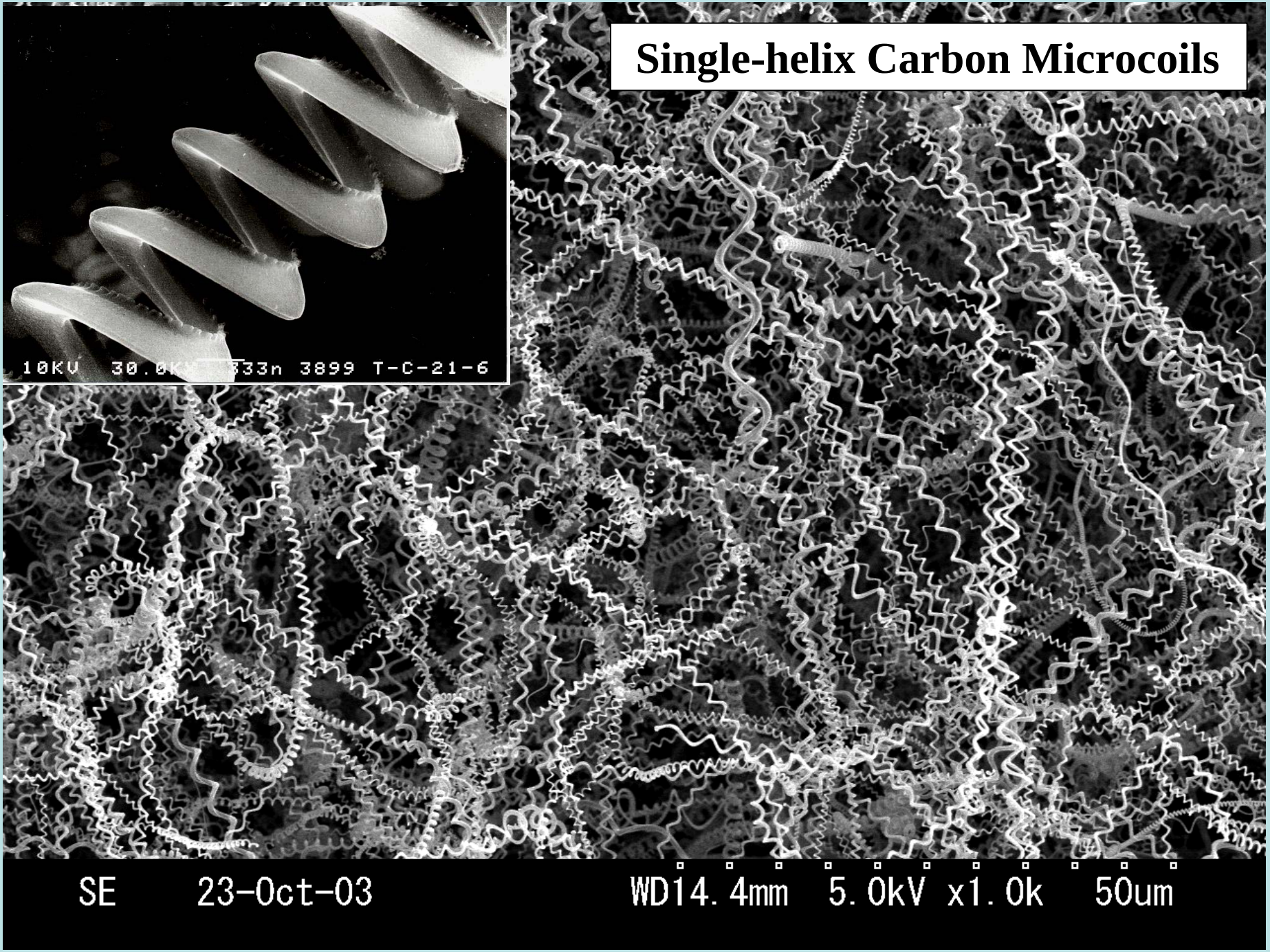


Regular Right-hand Carbon Microcoils

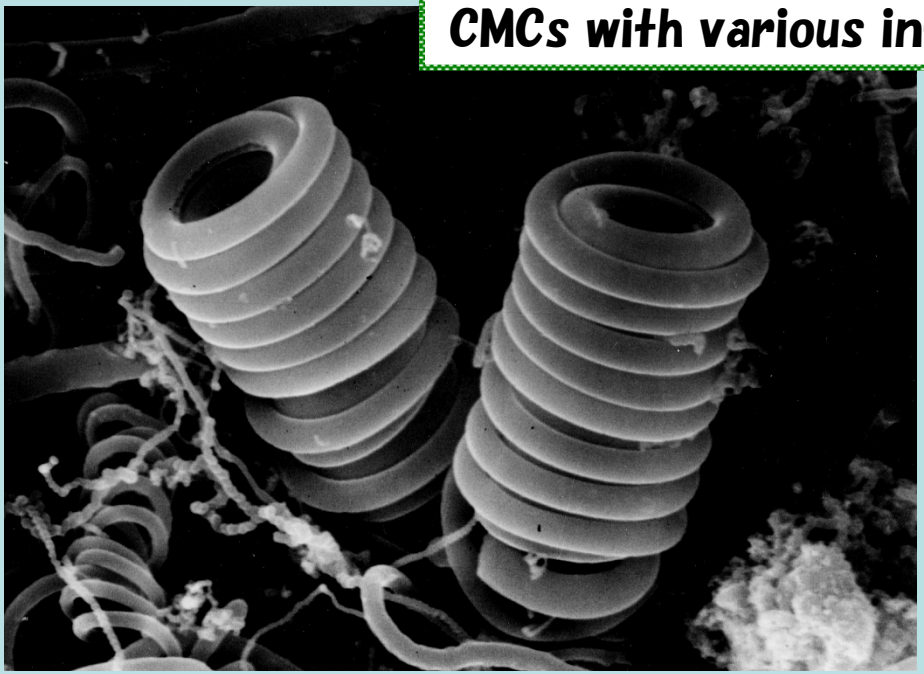


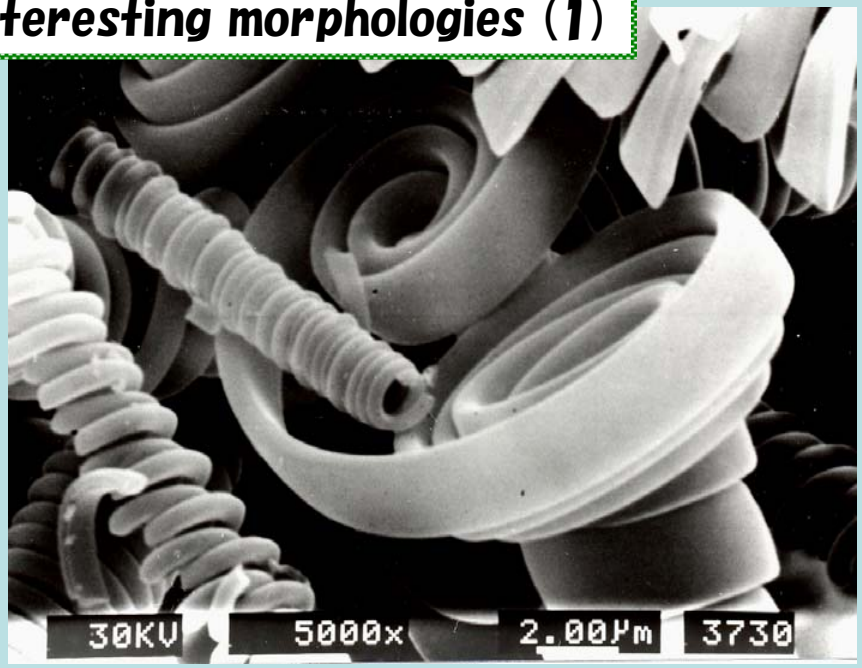
Regular left-hand Carbon Microcoils

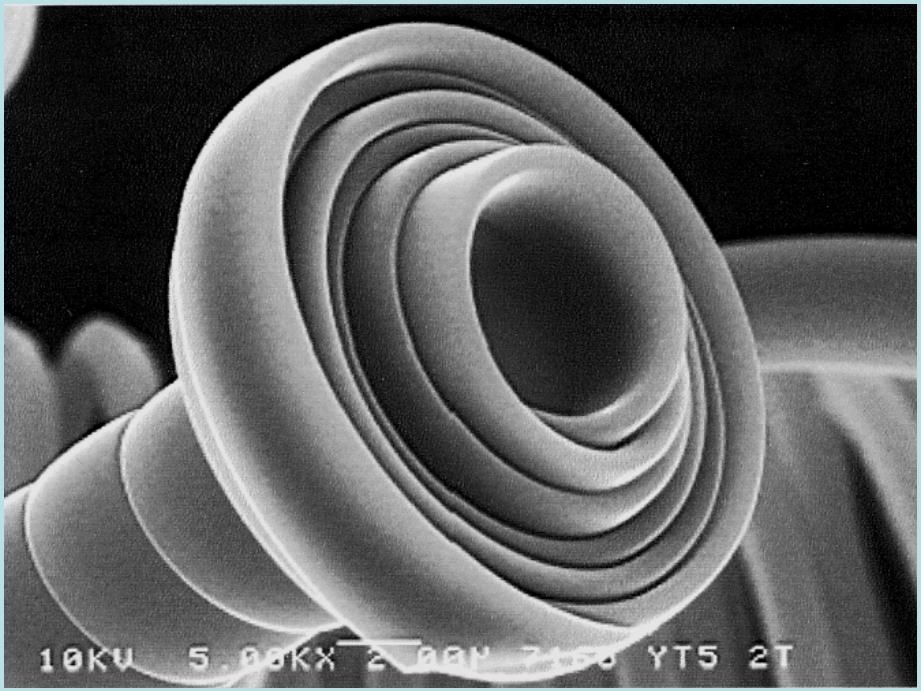
Single-helix Carbon Microcoils

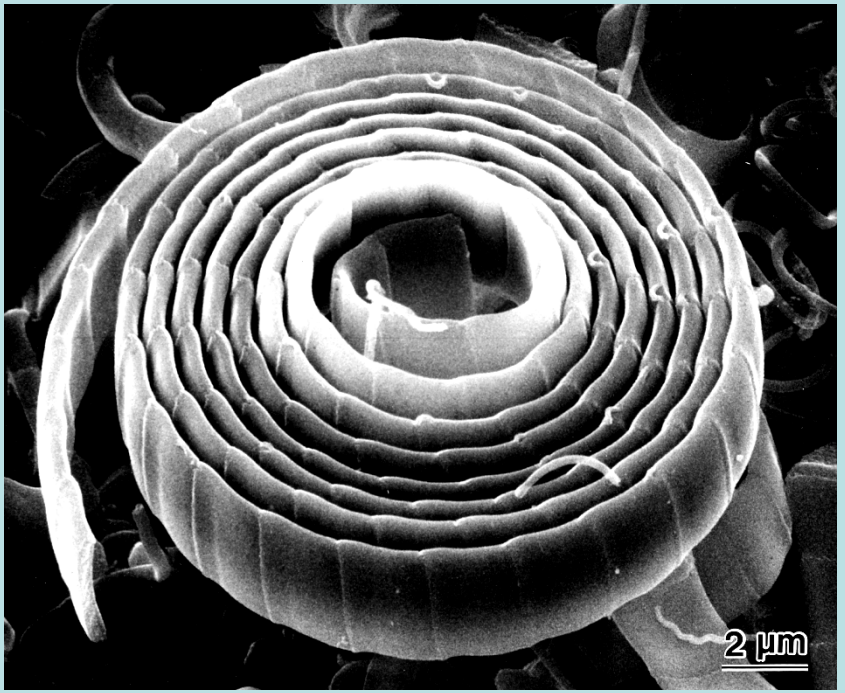


CMCs with various interesting morphologies (1)

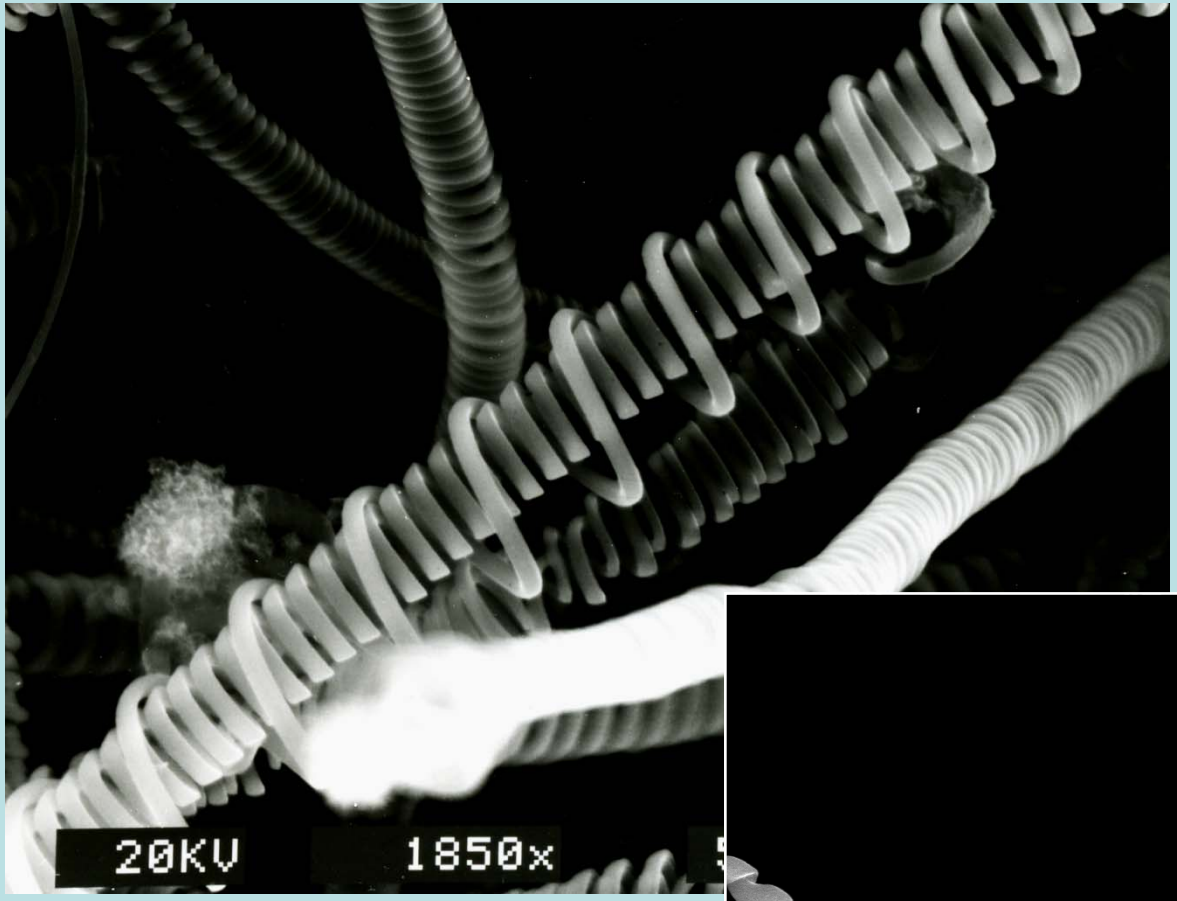


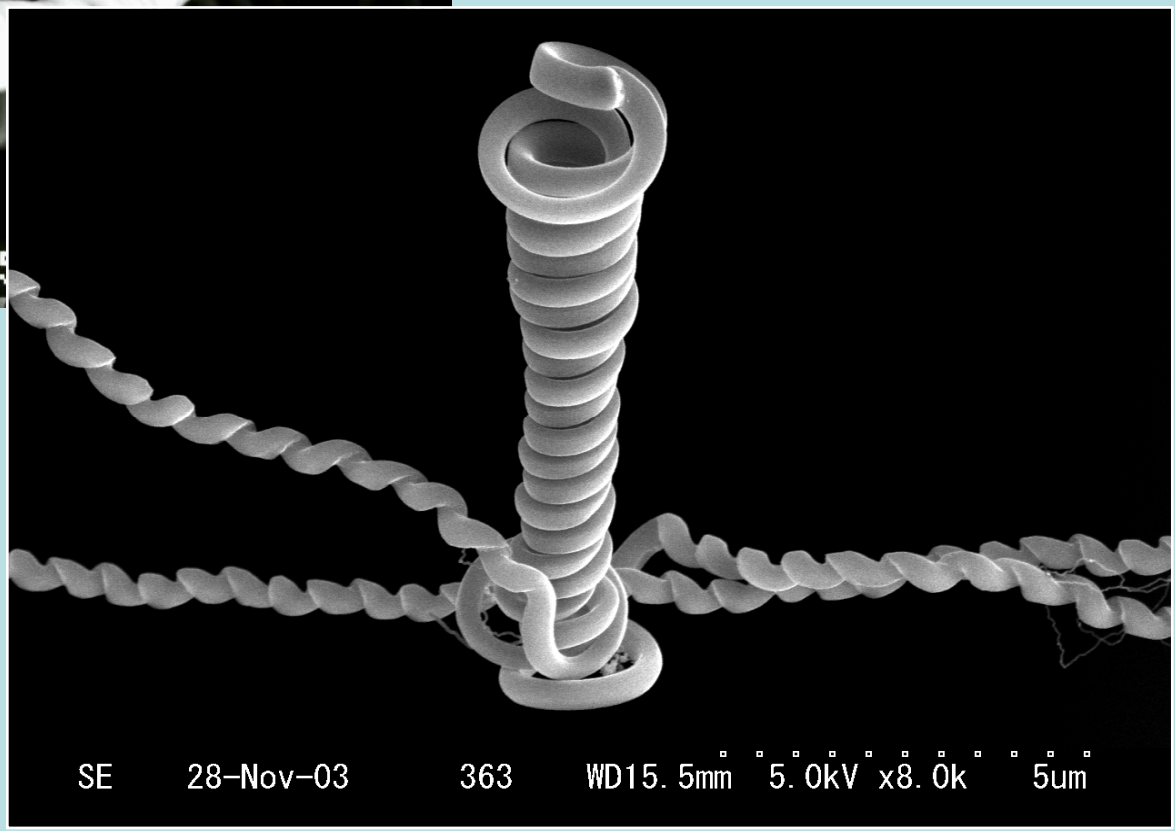






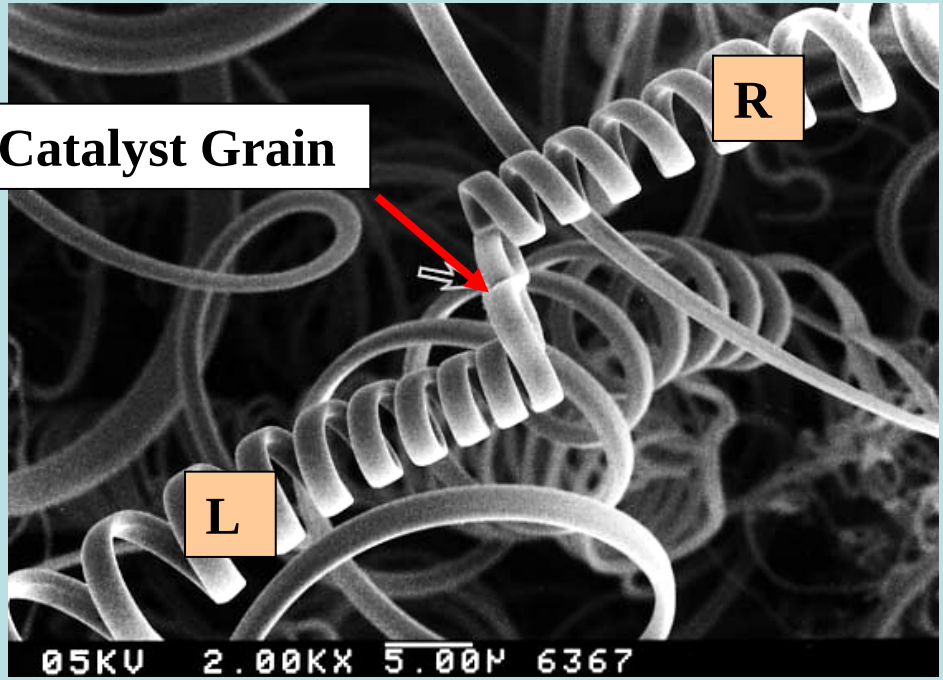
CMCs with various interesting morphologies (2)

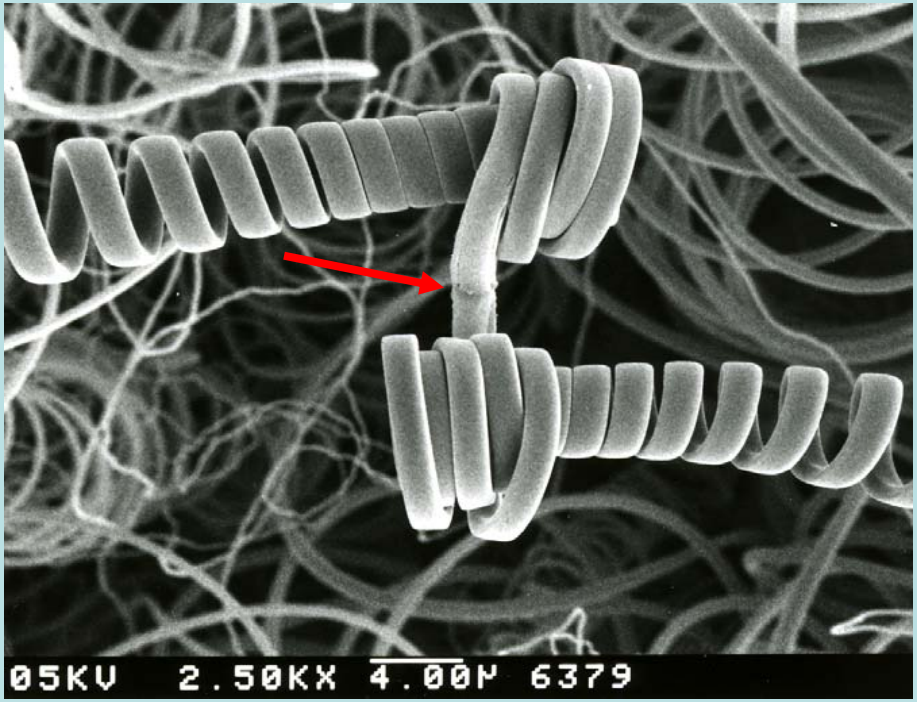


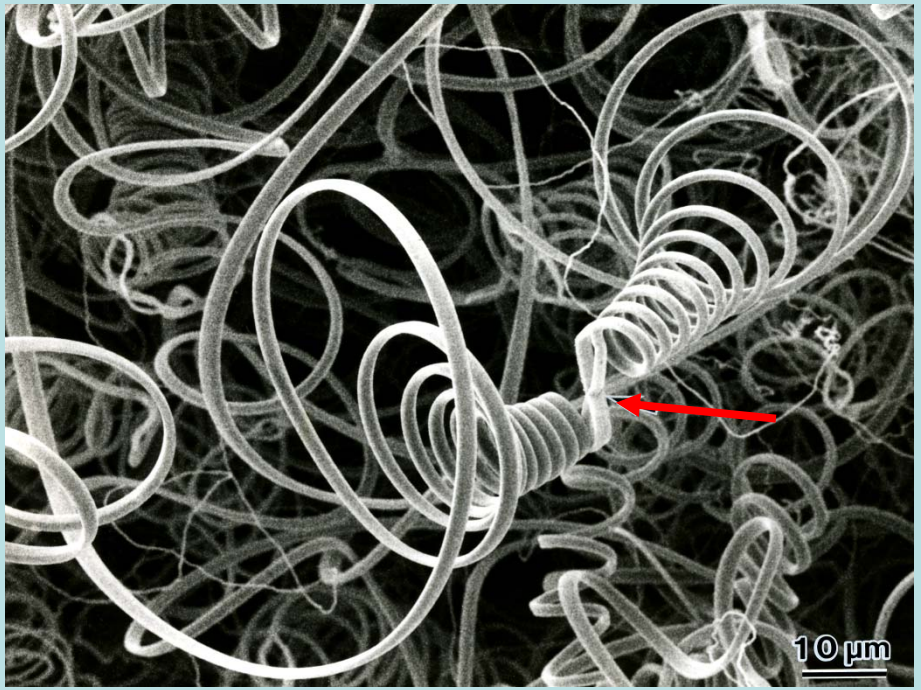


Twinned single-helix CMC grown from a catalyst grain

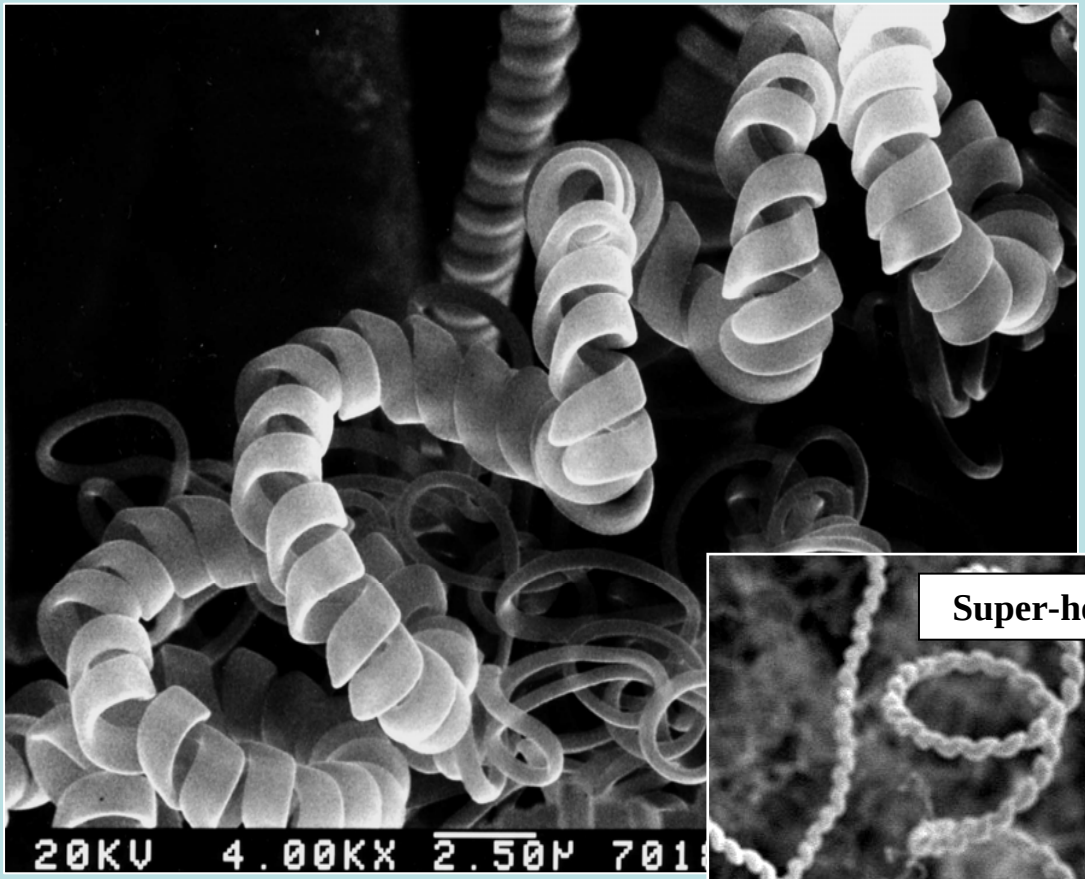
Arrow indicate a catalyst grain

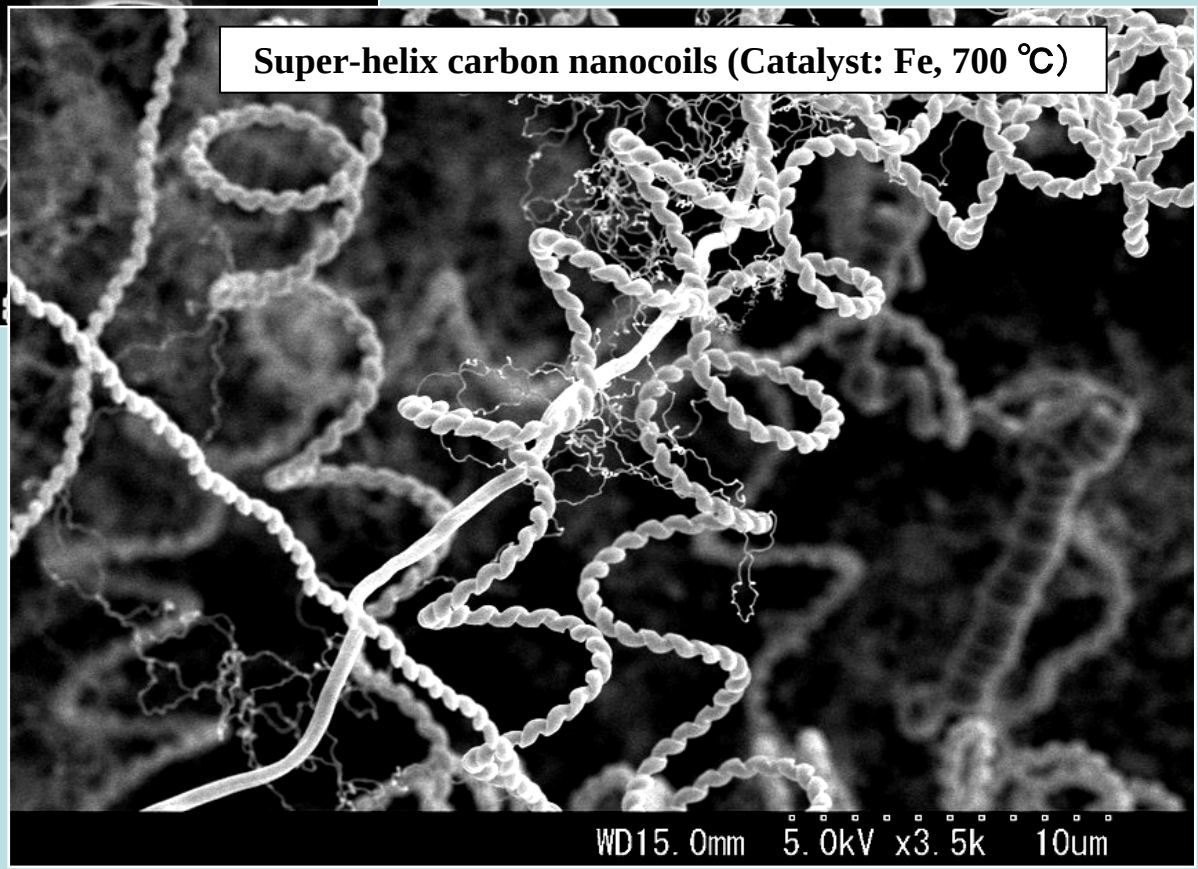


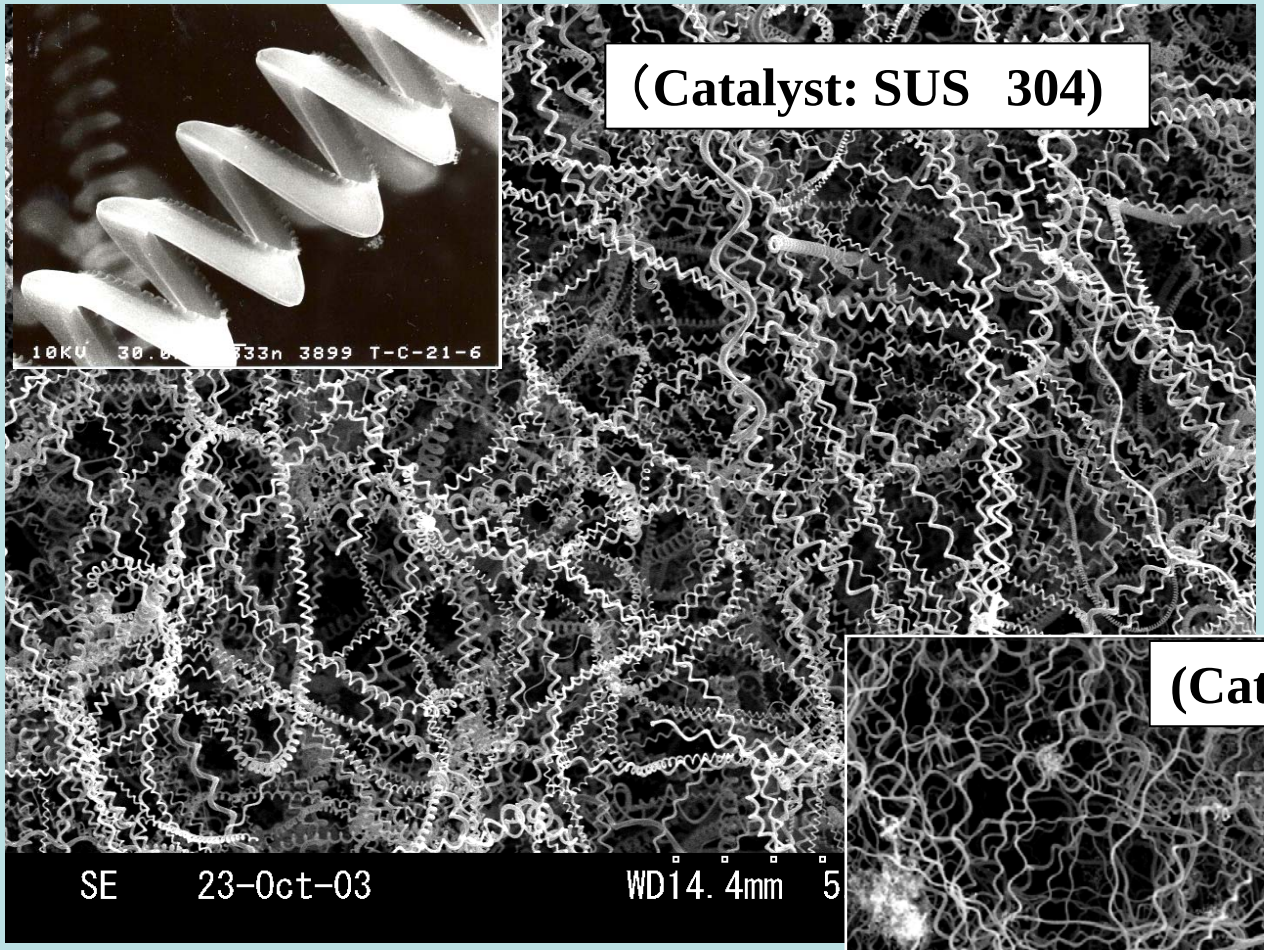




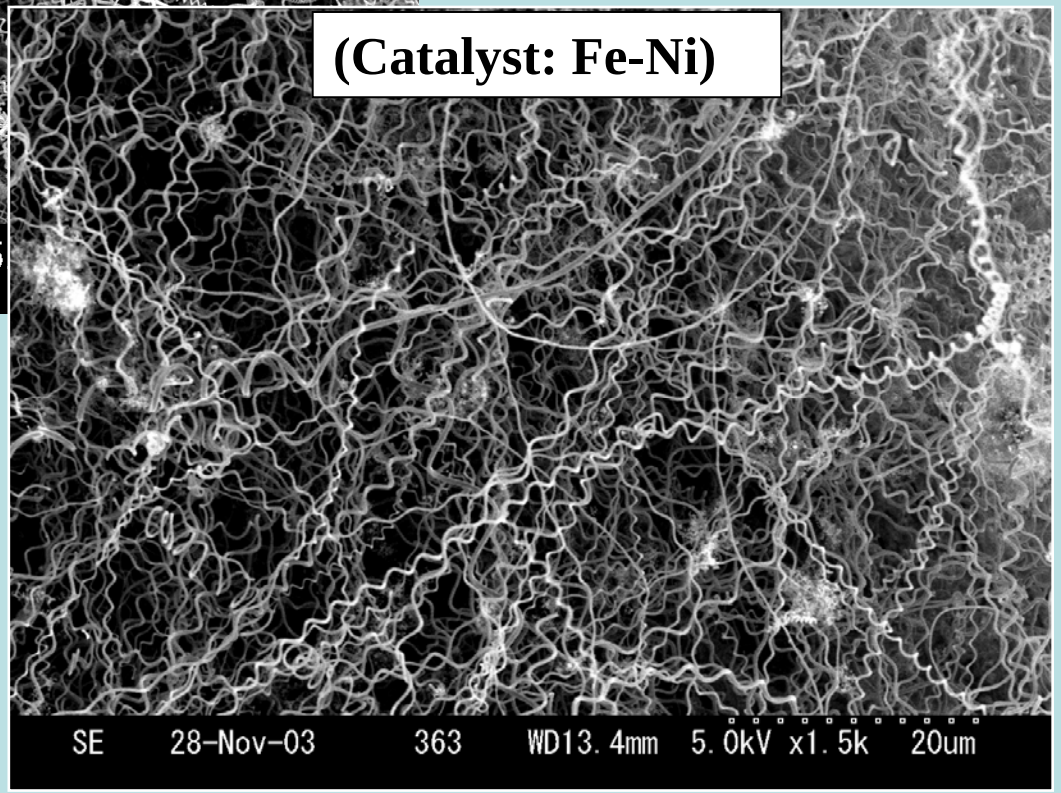
Super-helix CMC



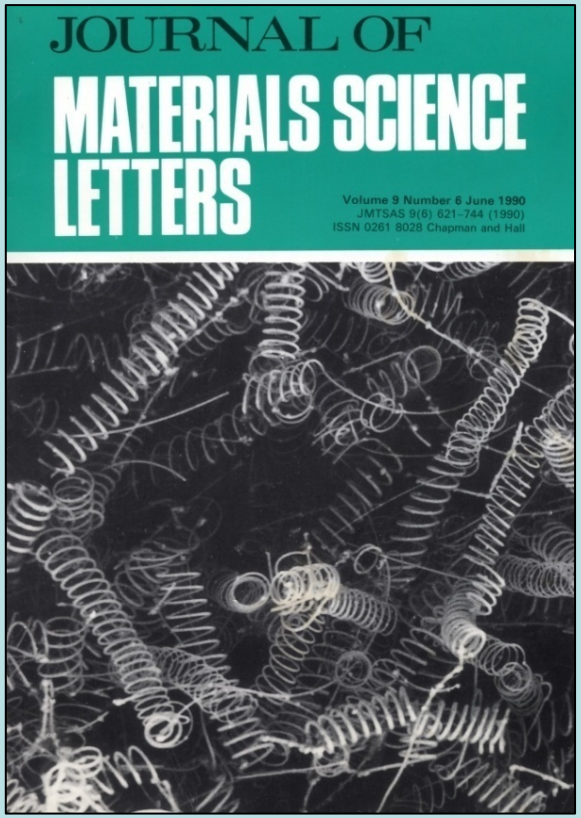


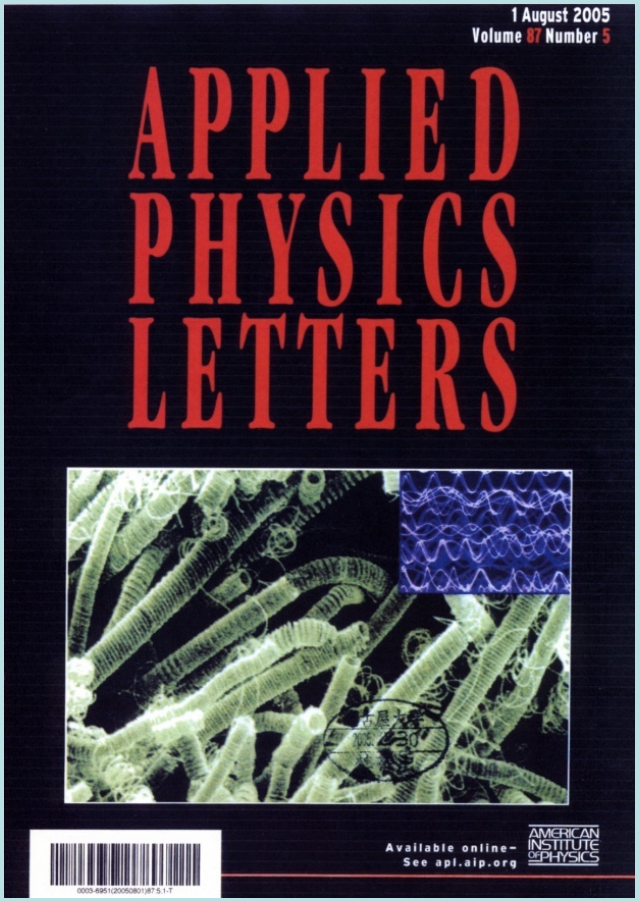


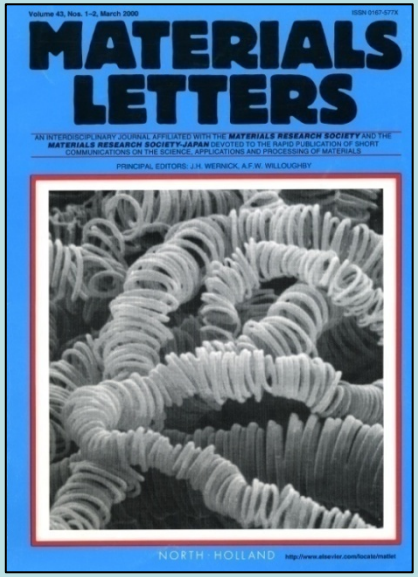
Single-helix CMC



Cover photographs of Journals

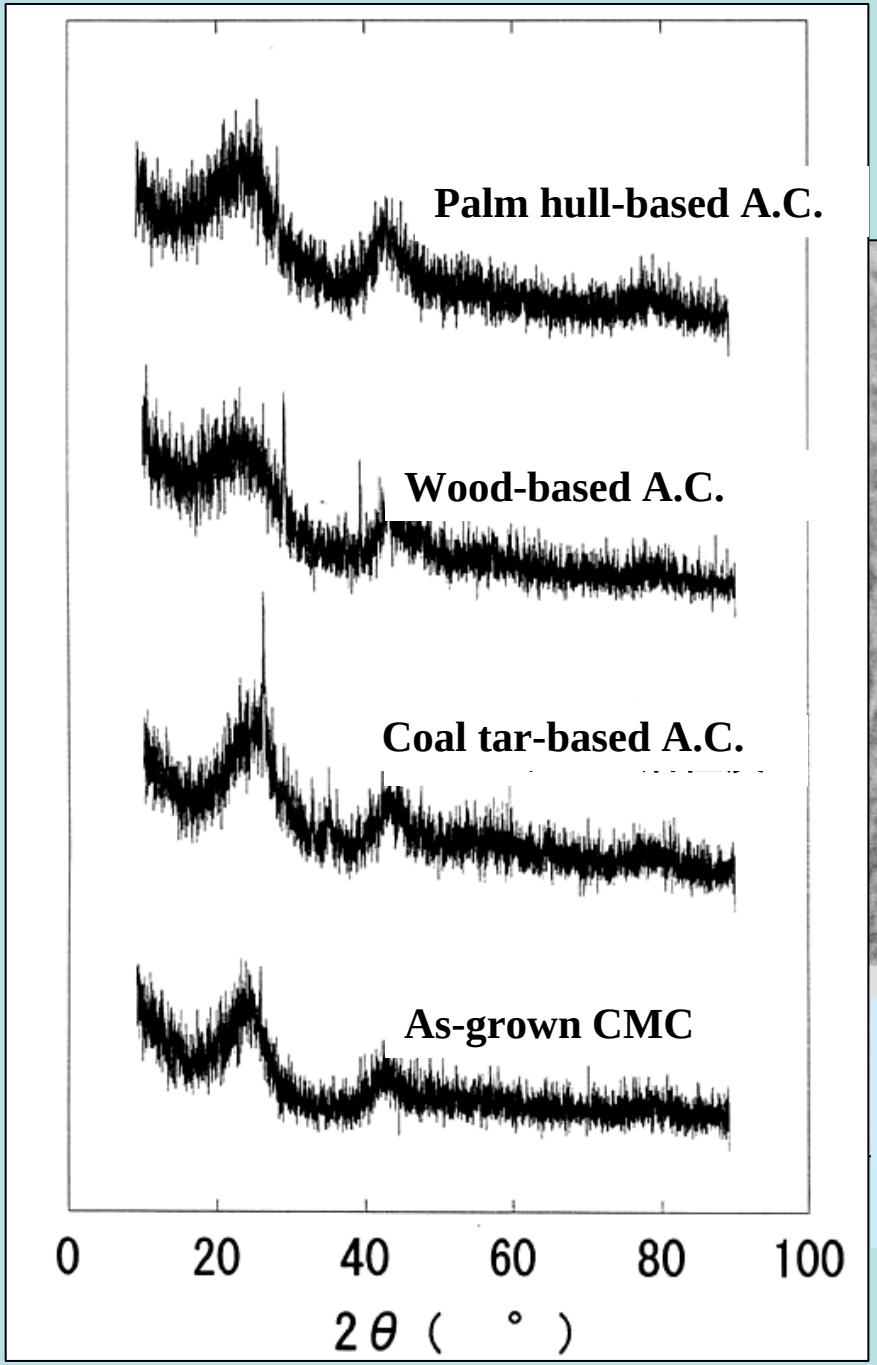




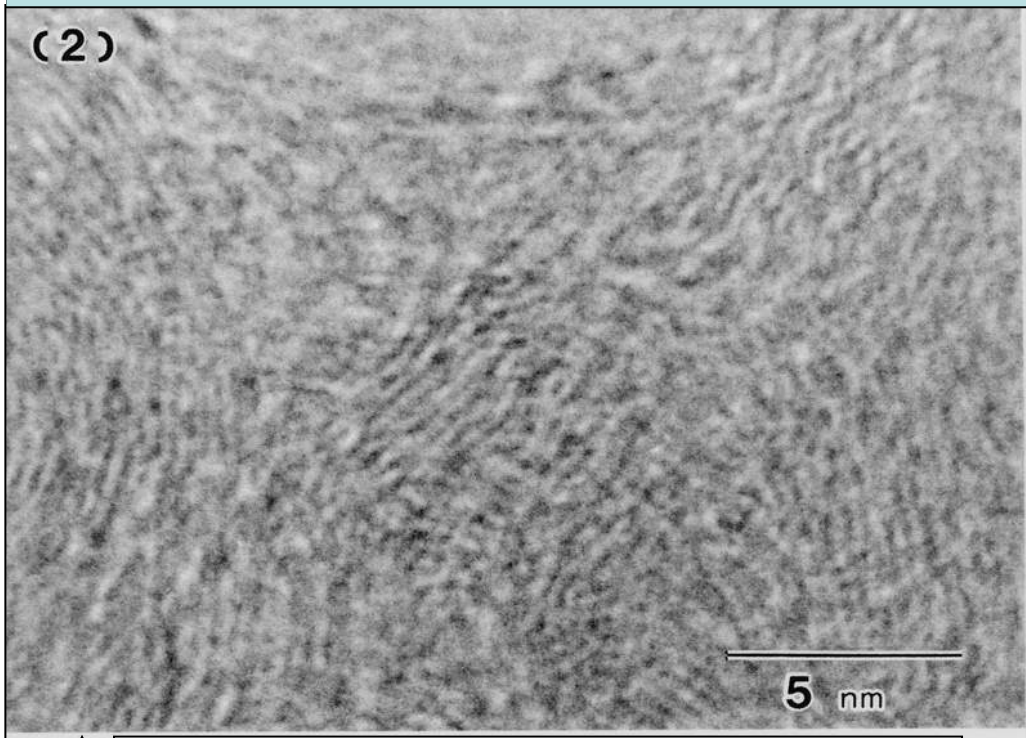


These interesting micrographs were published as cover photographs of international journals.

Microstructure of as-grown CMC

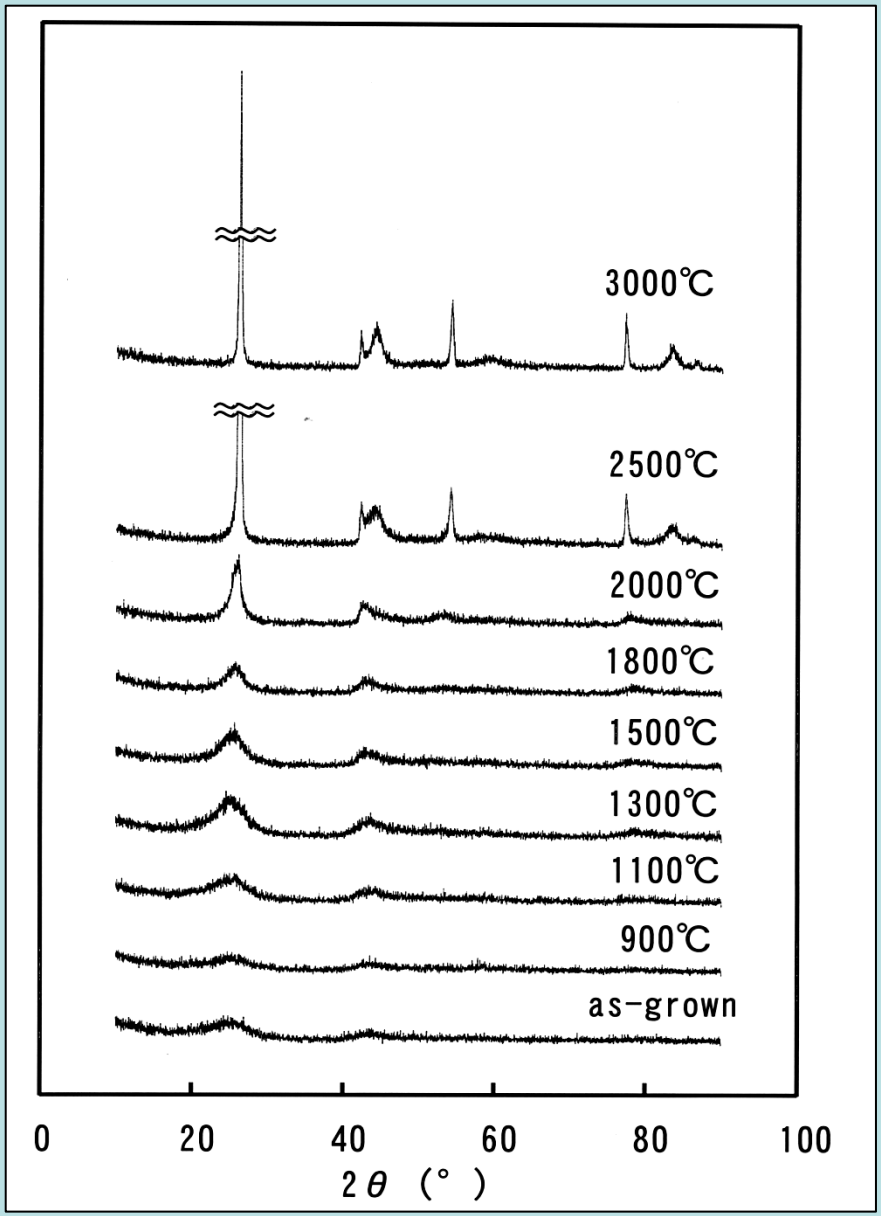


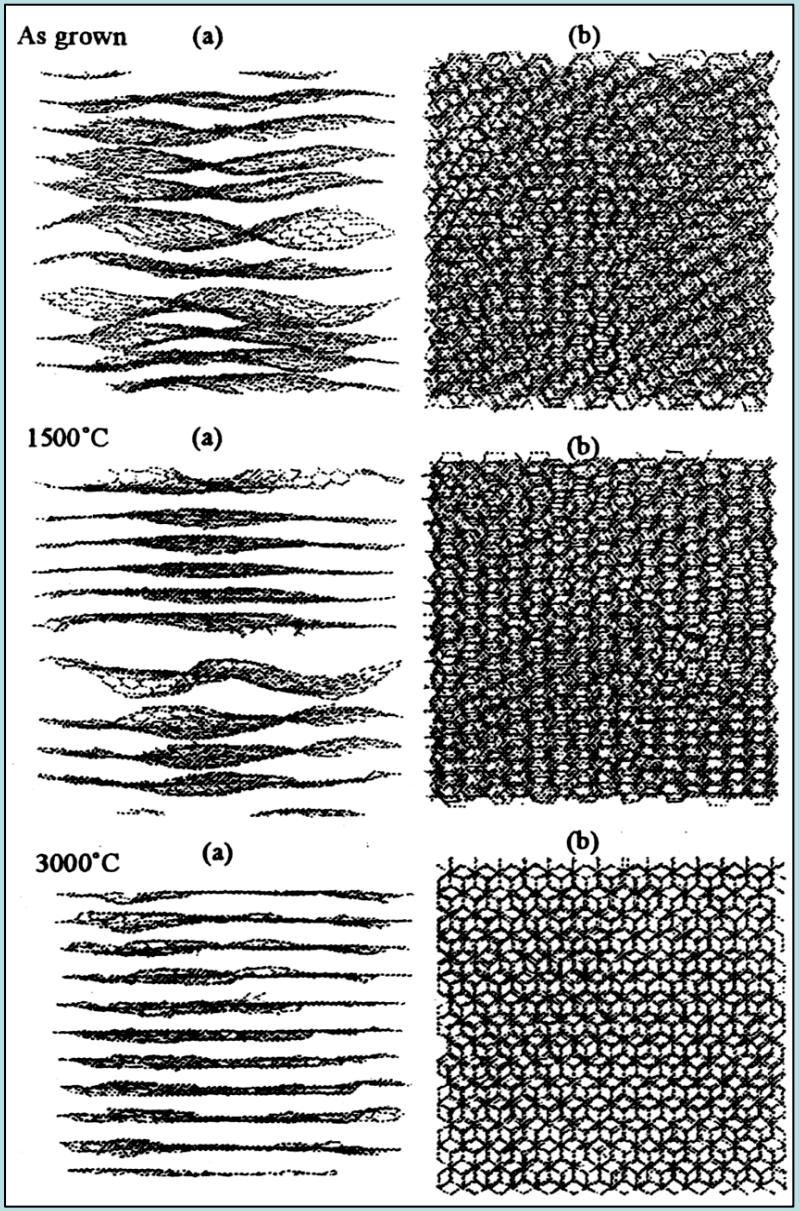
XRD pattern of as-grown CMC and activated carbon



TEM (lattice) image of as-grown CMC

XRD patterns (left) and Neutron diffraction analysis (right) of as-grown CMC and heat-treated CMC in $CO+CO_2$ or Ar atmosphere





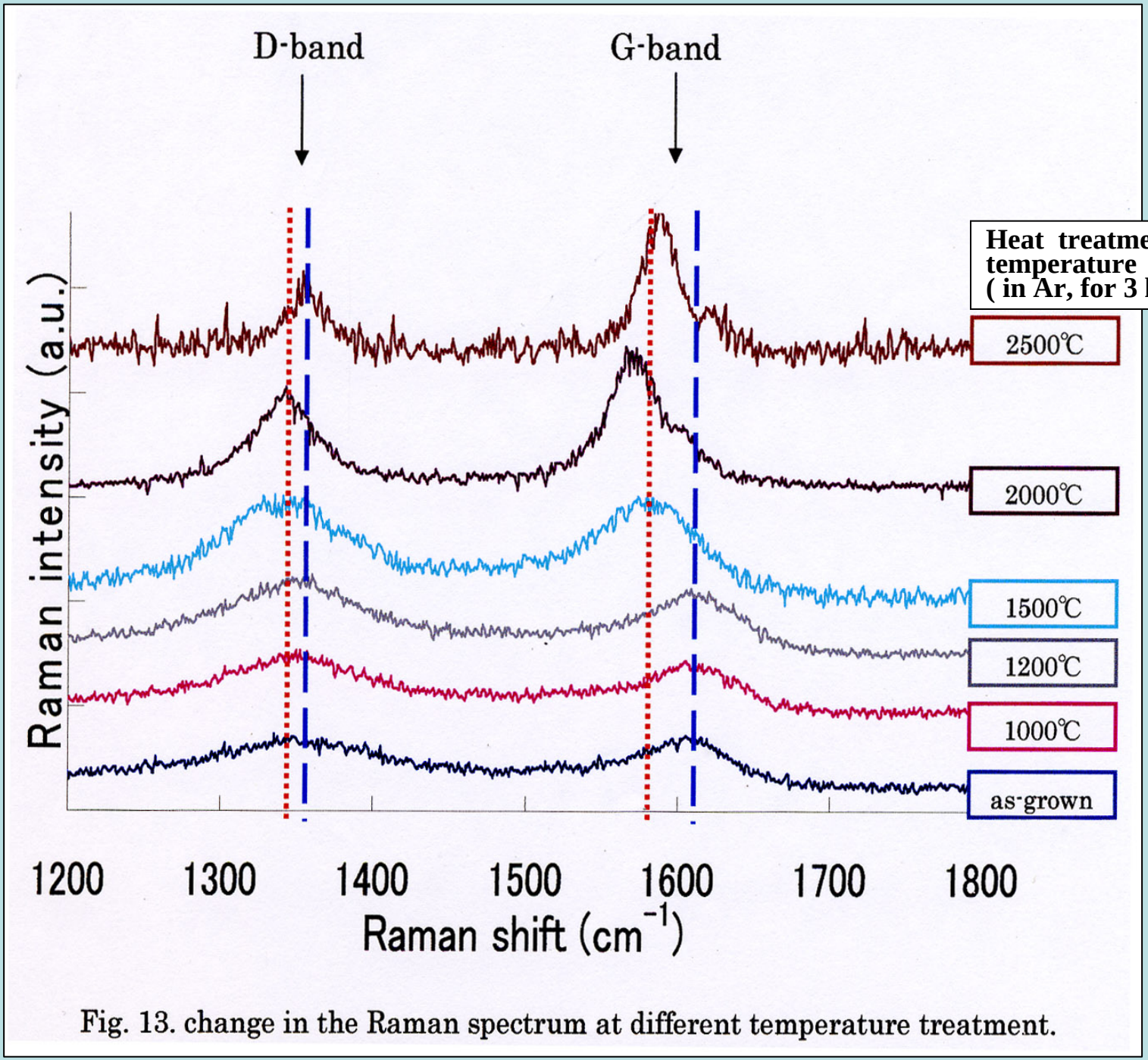
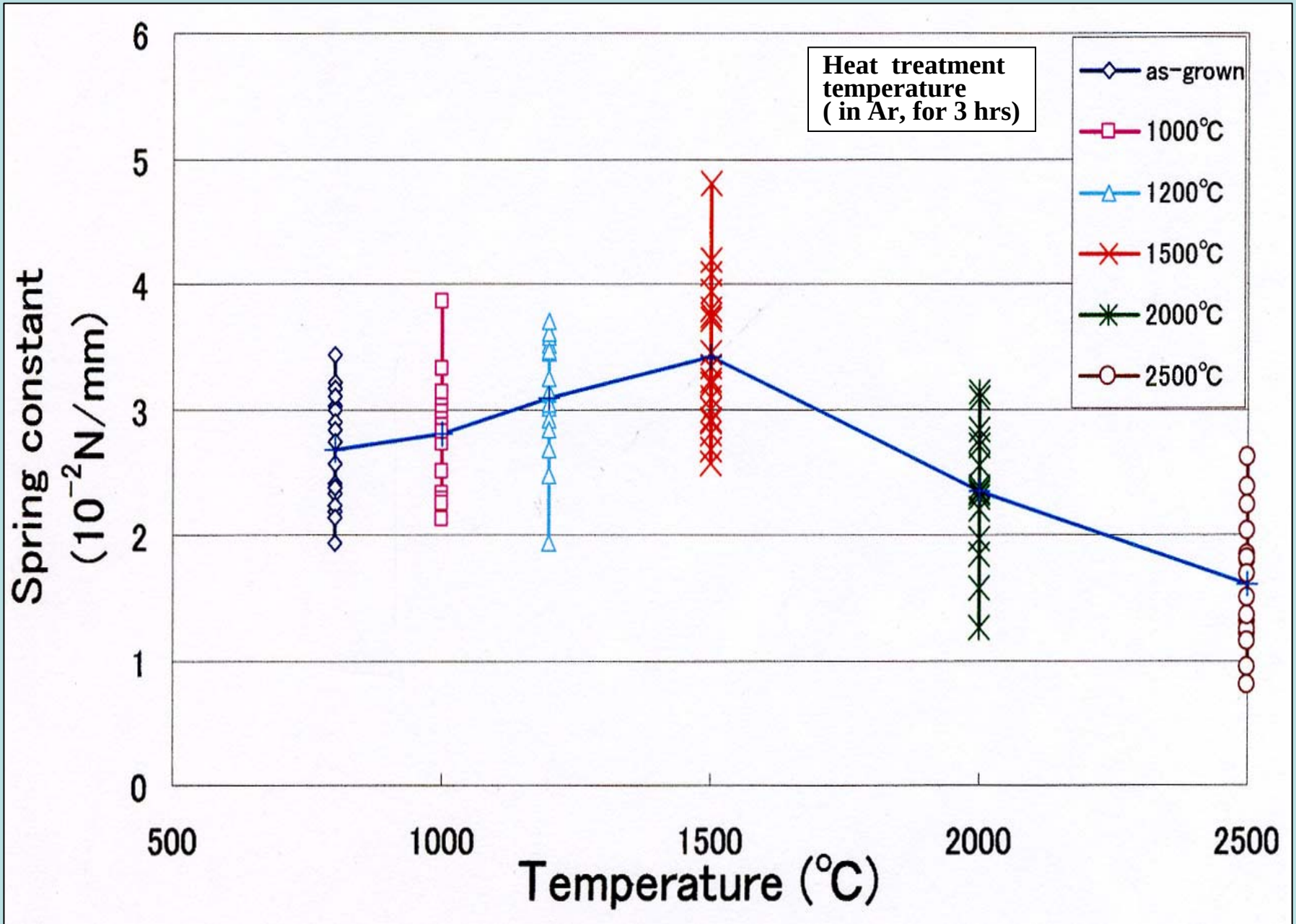


Fig. 13. change in the Raman spectrum at different temperature treatment.

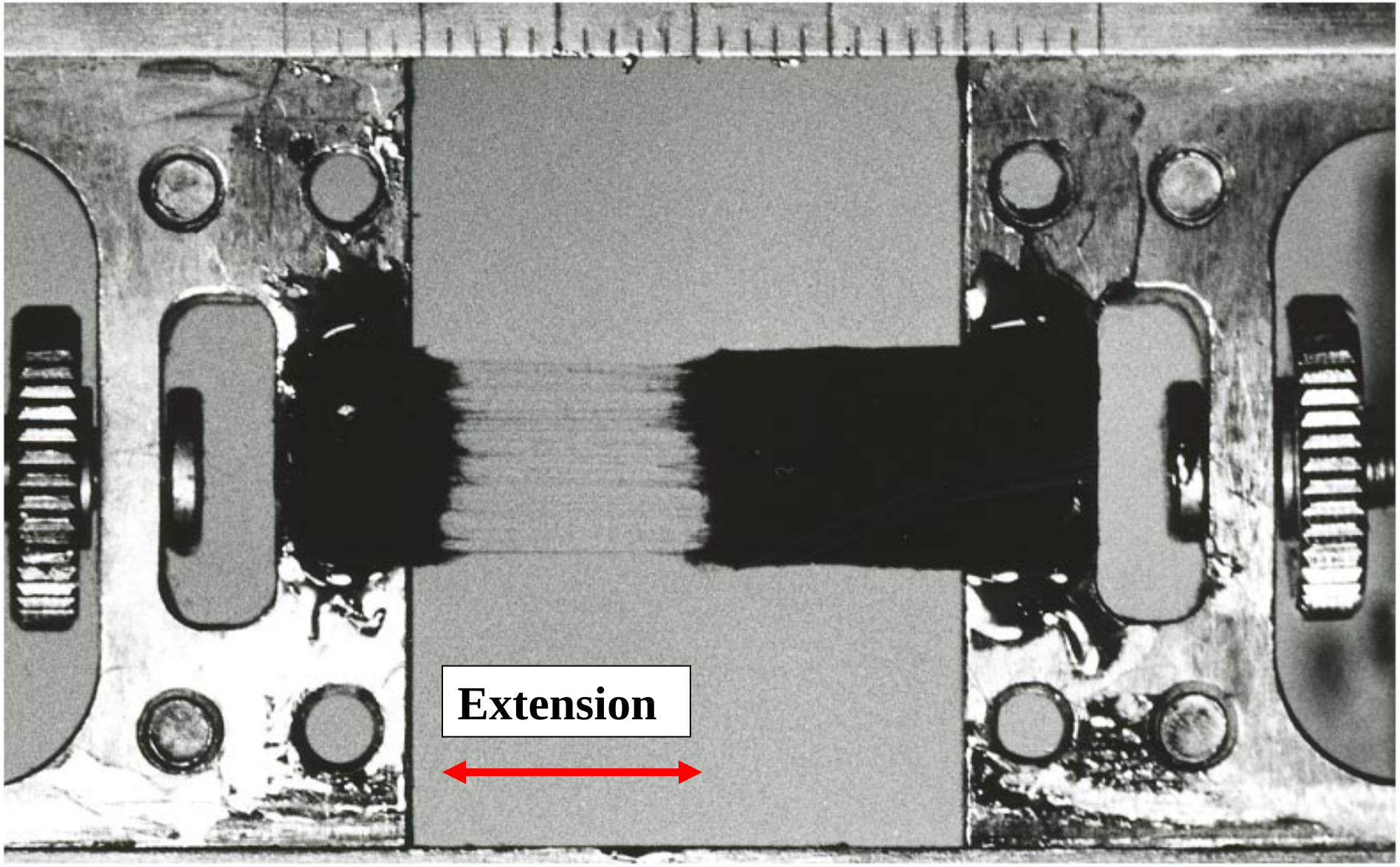
Influence of heat-treatment temperature on the spring constant



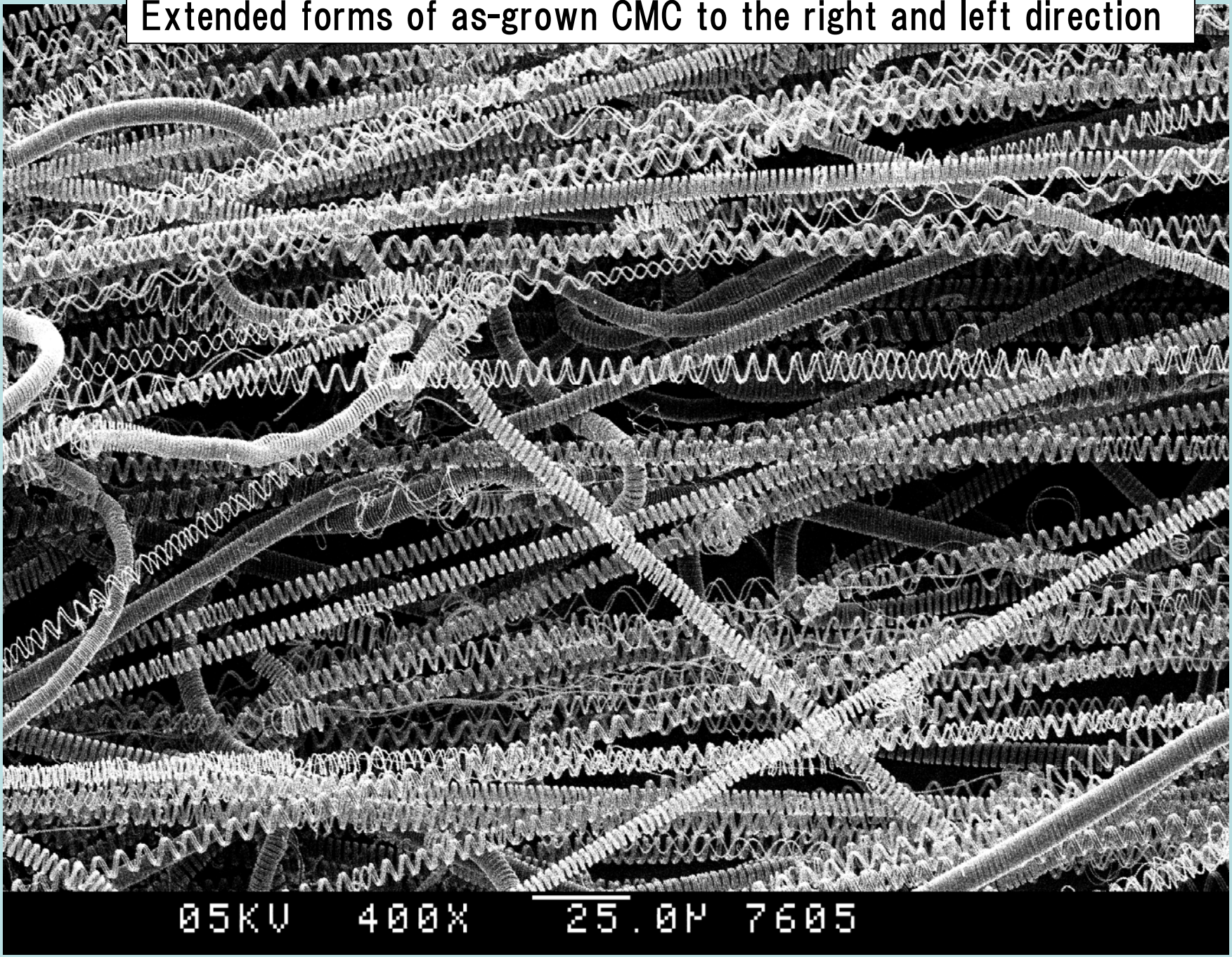
Videos showing the extension and contraction of as-grown CMC

A piece of CMC

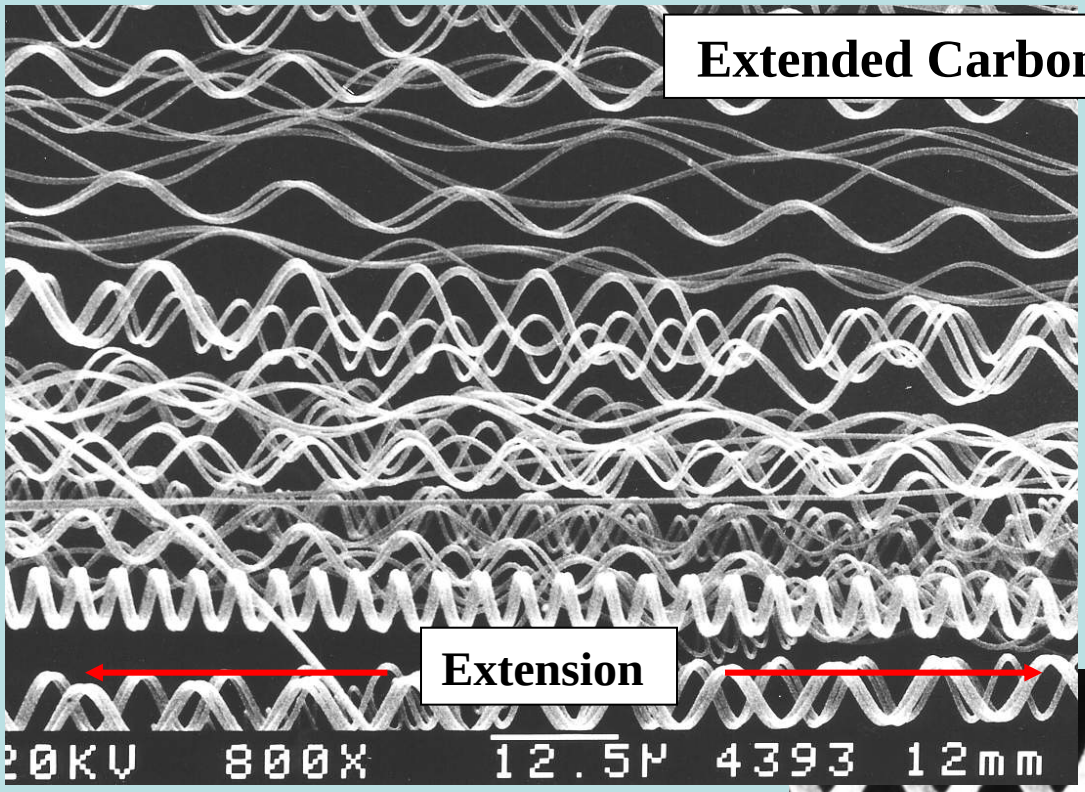
Bulk CMC as-grown on the substrate

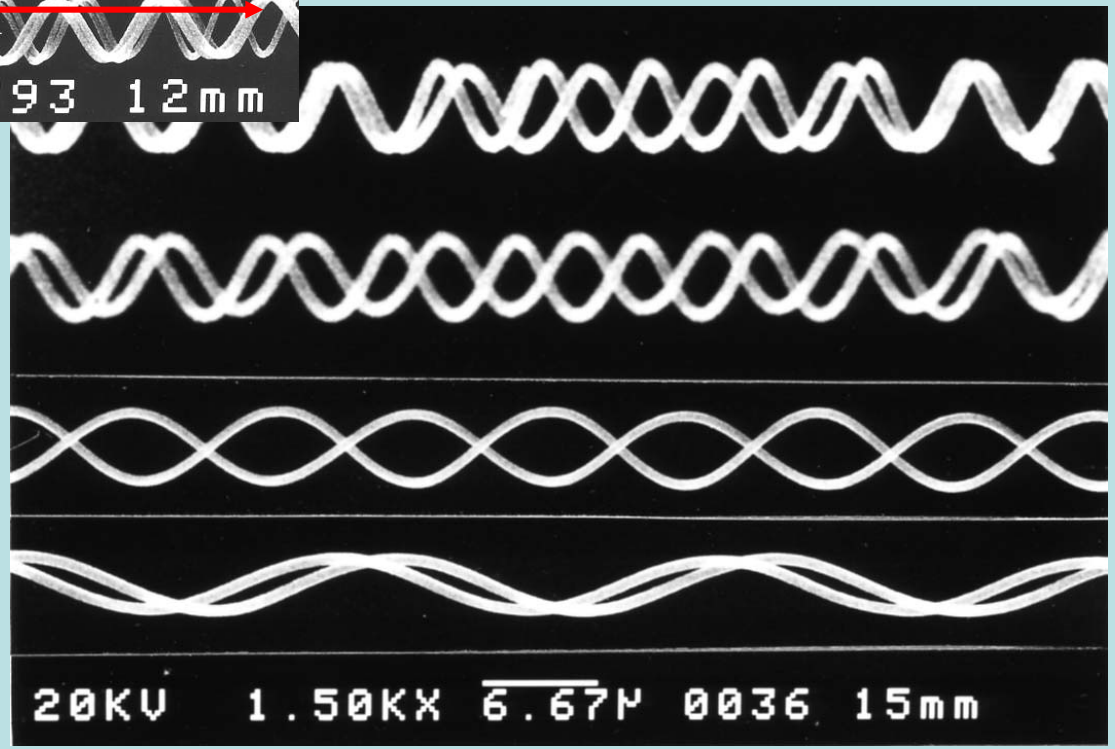

Extension

Extended forms of as-grown CMC to the right and left direction



Extended Carbon Microcoils

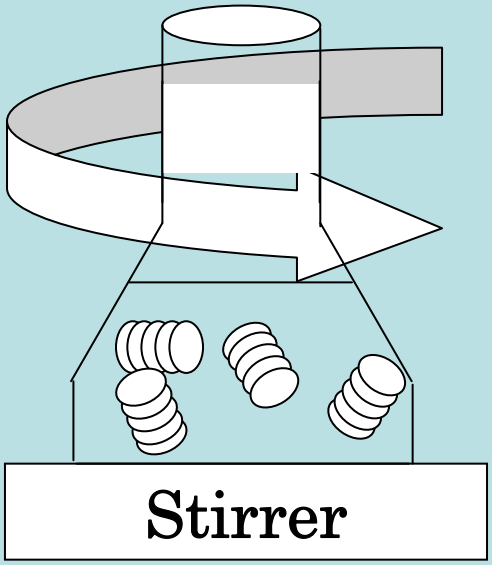


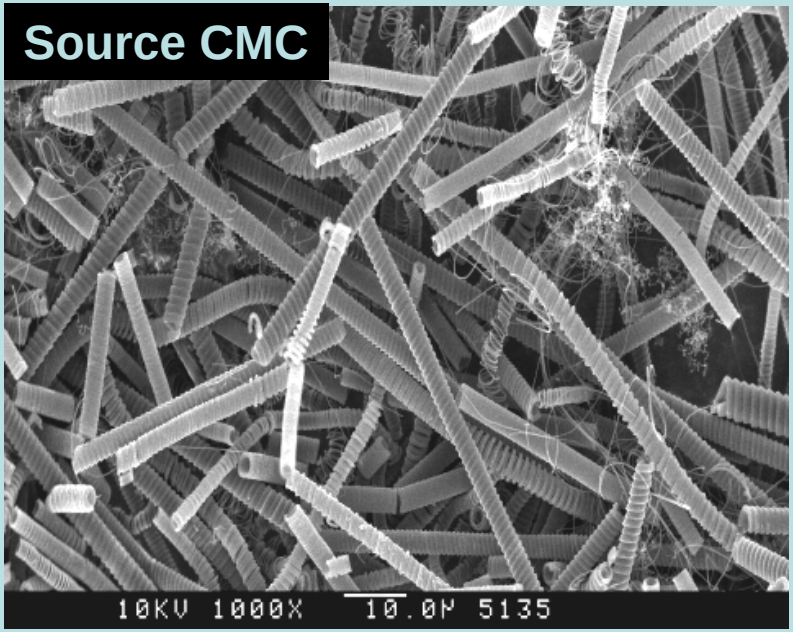


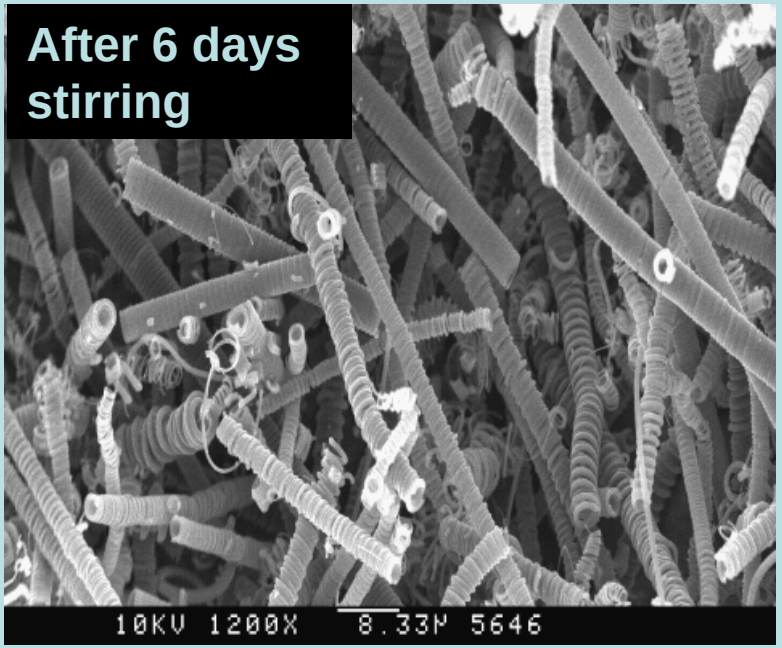
Mechanical stability of CMC

Characterization process

CMC（0.3g）/1,2-Dichloroethane（60ml）
stirred by magnetic stirrer in conical beaker (100ml)
for 6 days

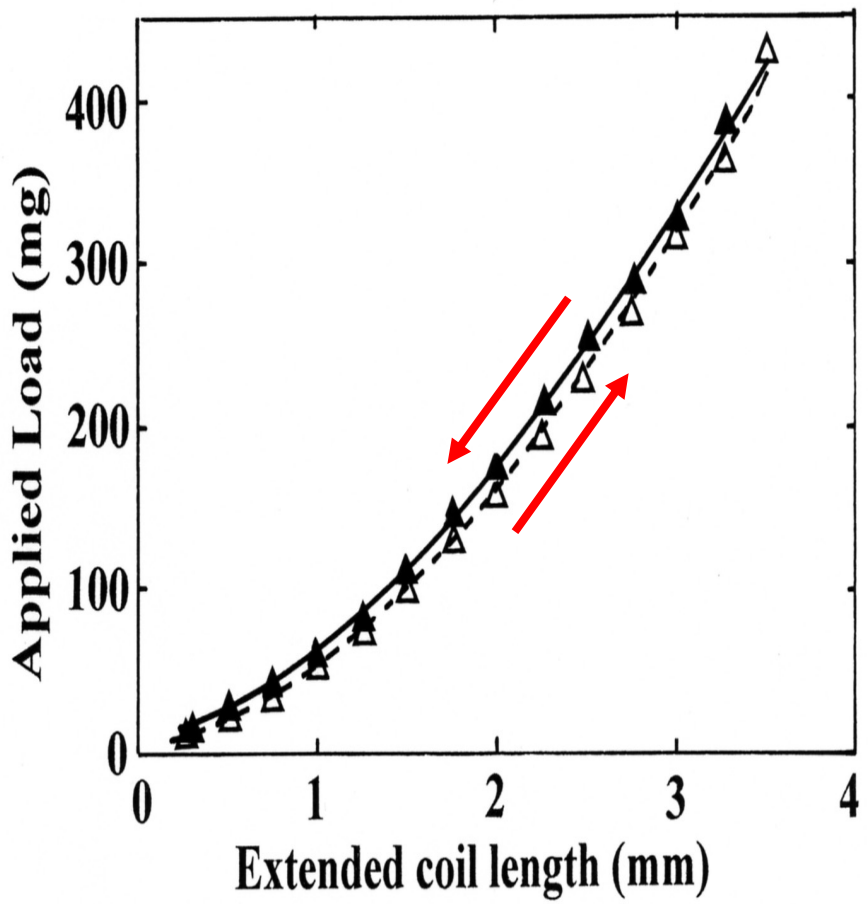




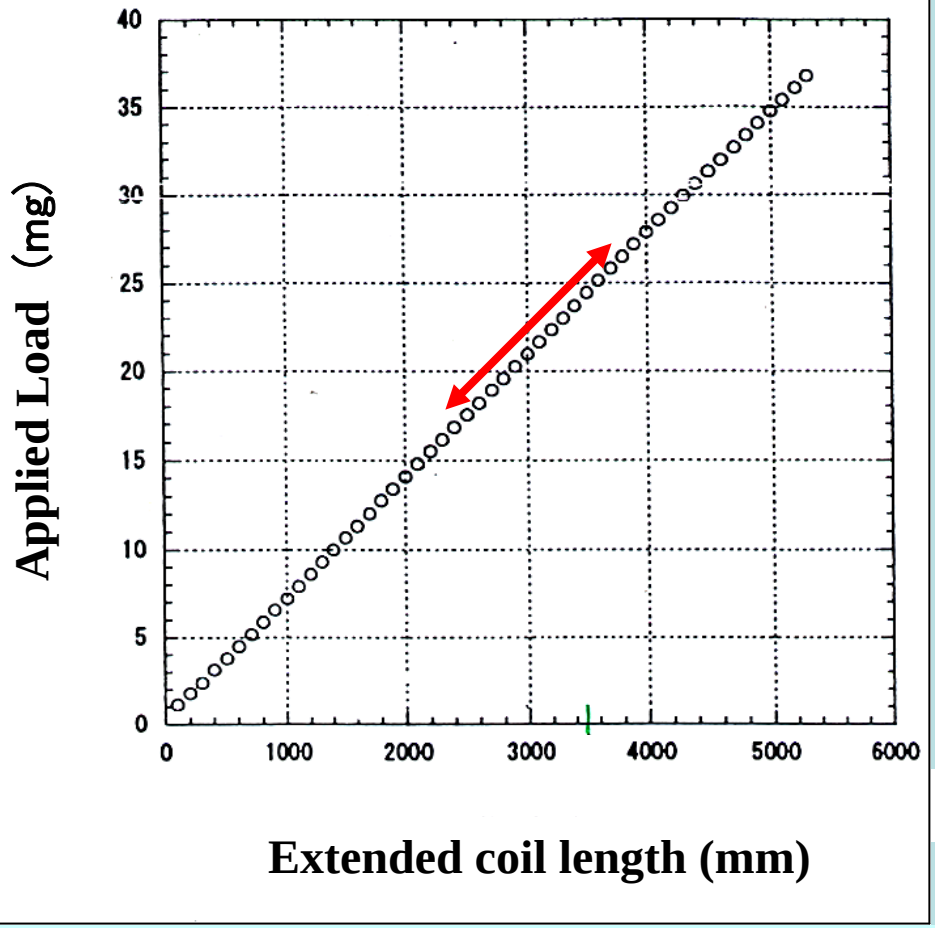


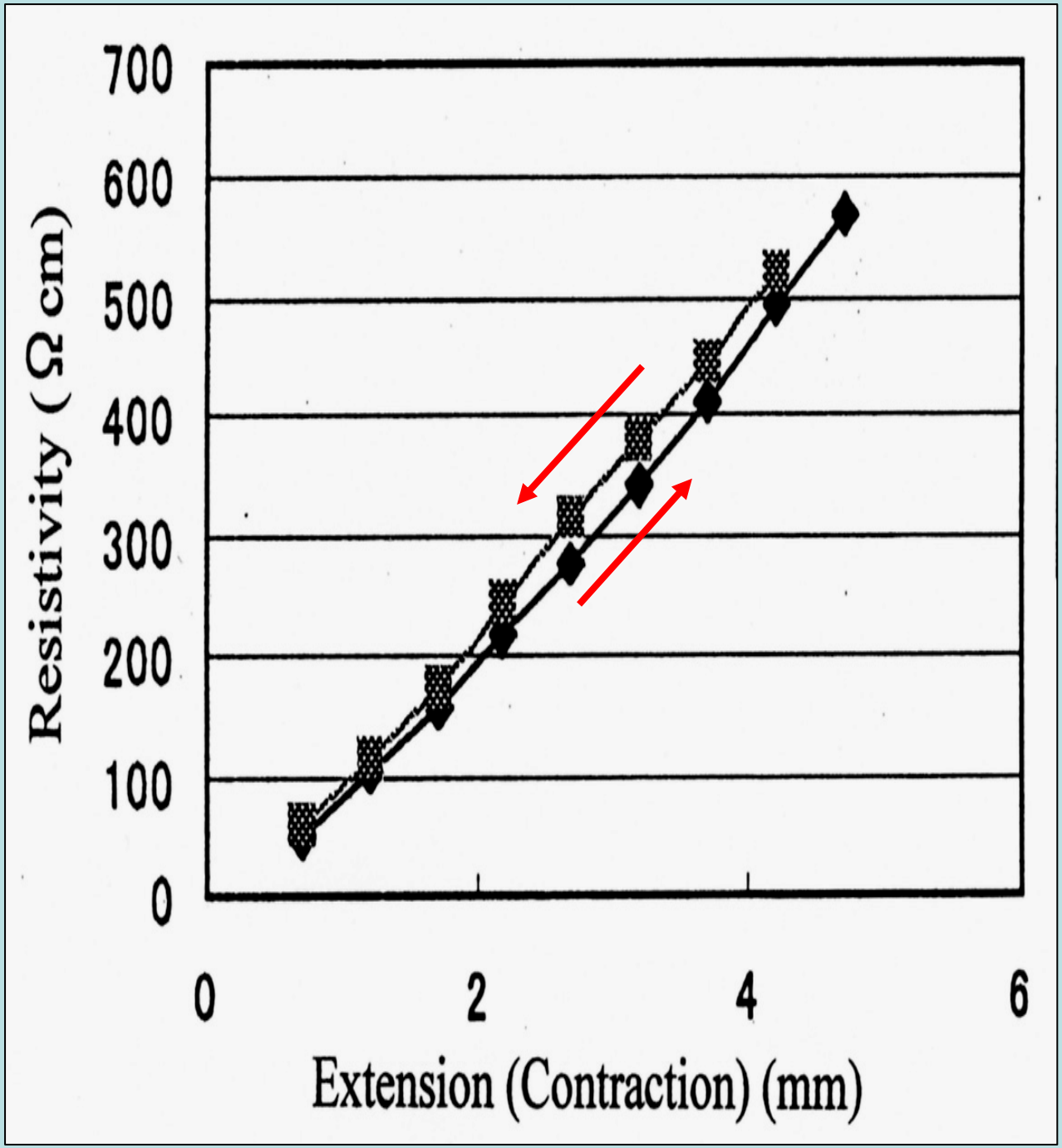
S-s curves of CMC under applied load

for Bulk coils



For a single coil





Another important characteristics of CMC is changing in electrical parameters under the extension or contraction of the coils。This figure shows the relationship between the extension and electrical resistivity.

It can be seen that the electrical resistivity increases with the extension and decrease with the contraction. Other electrical parameter, such as L, C, Z, θ also changes by the extension or contraction.

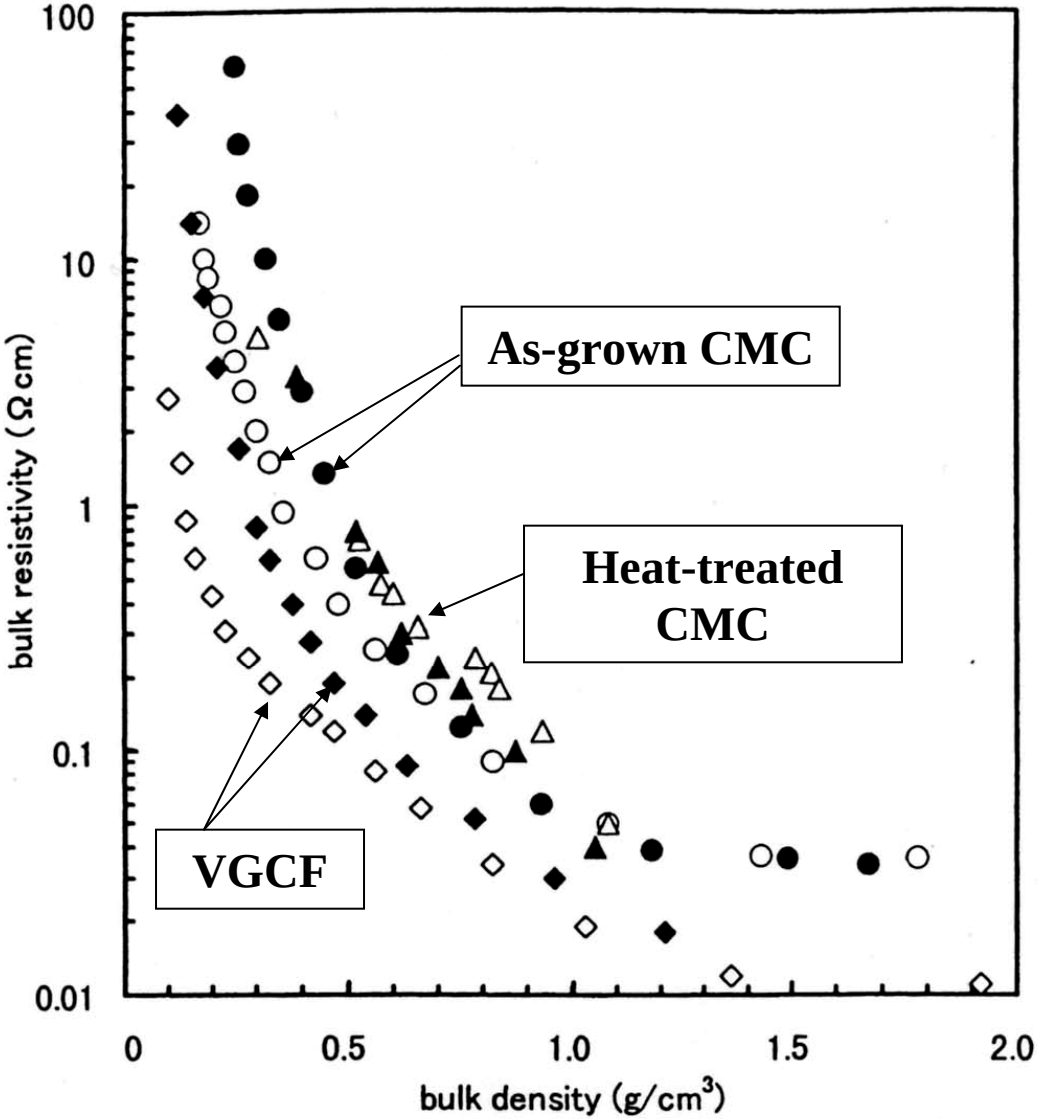


FIG. 15. Bulk electrical resistivity obtained at room temperature in air: (△) graphite coils (coil length >1 mm), (▲) graphite coils (coil length <1 mm), (○) as-grown carbon coils (coil length >1 mm), (●) as-grown carbon coils (coil length <1 mm), (◇) VFGCF (1), and (◆) VGCF (2).

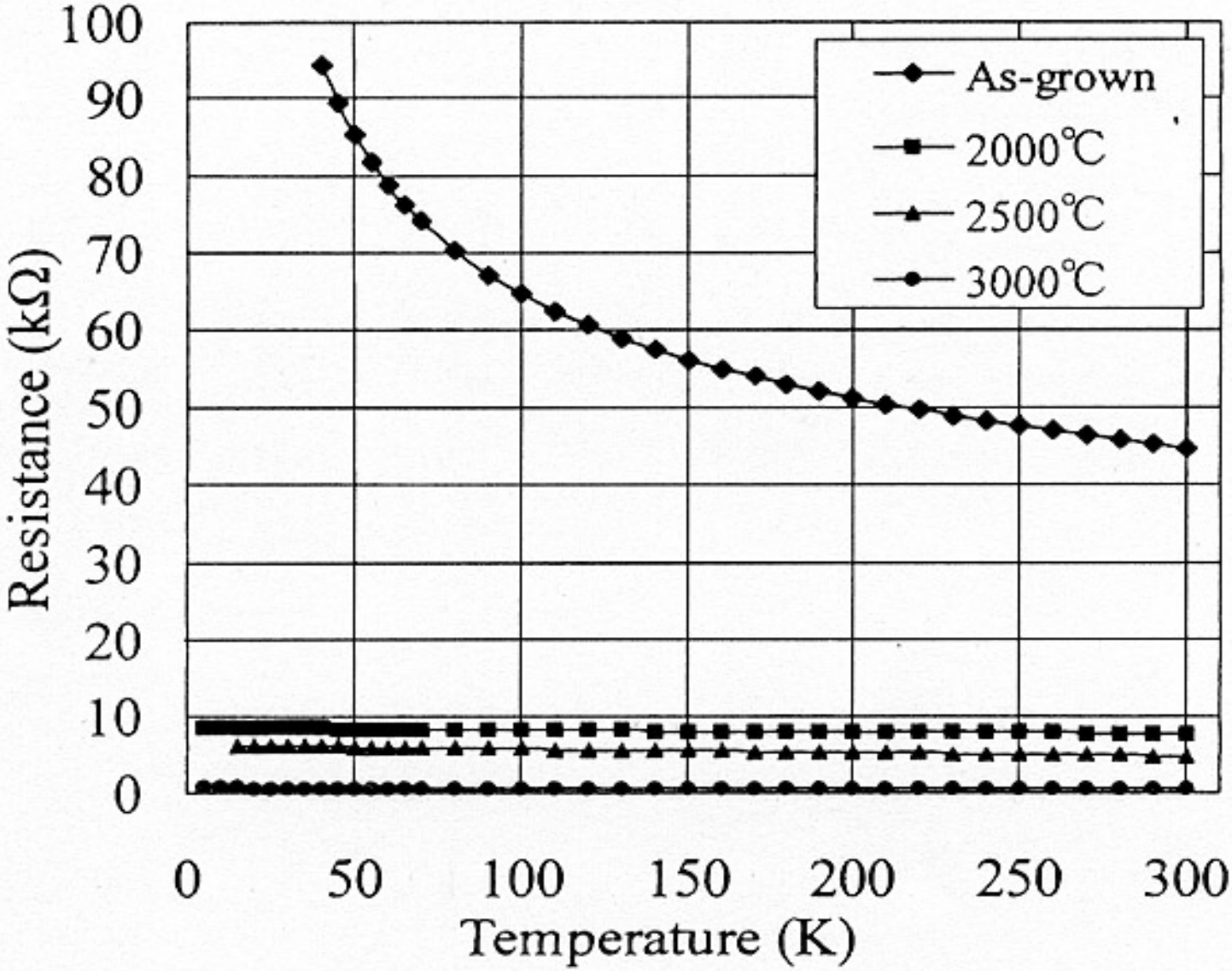
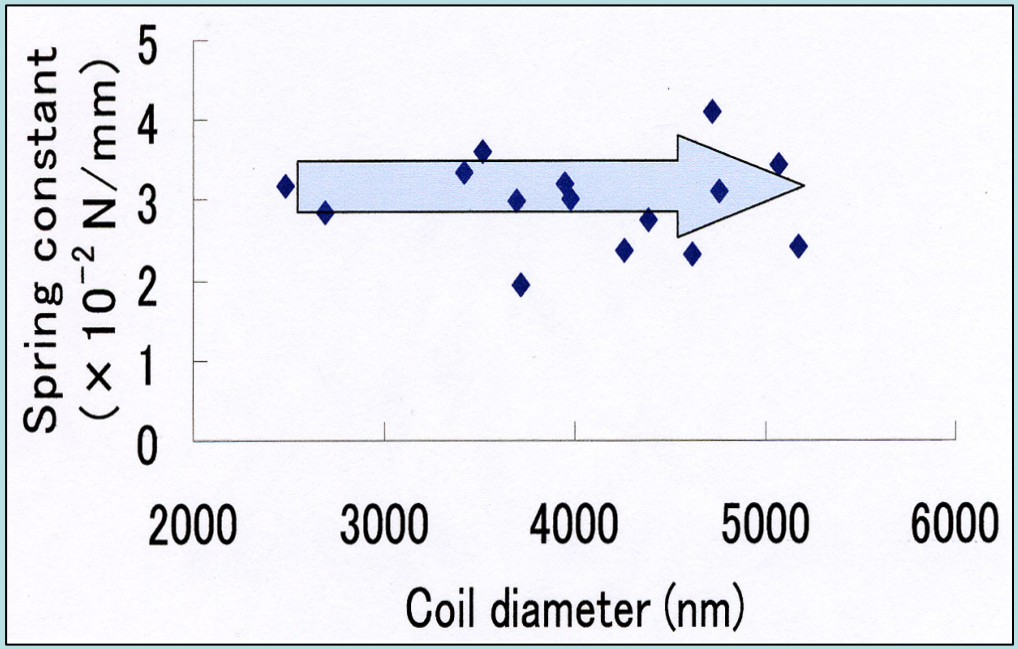
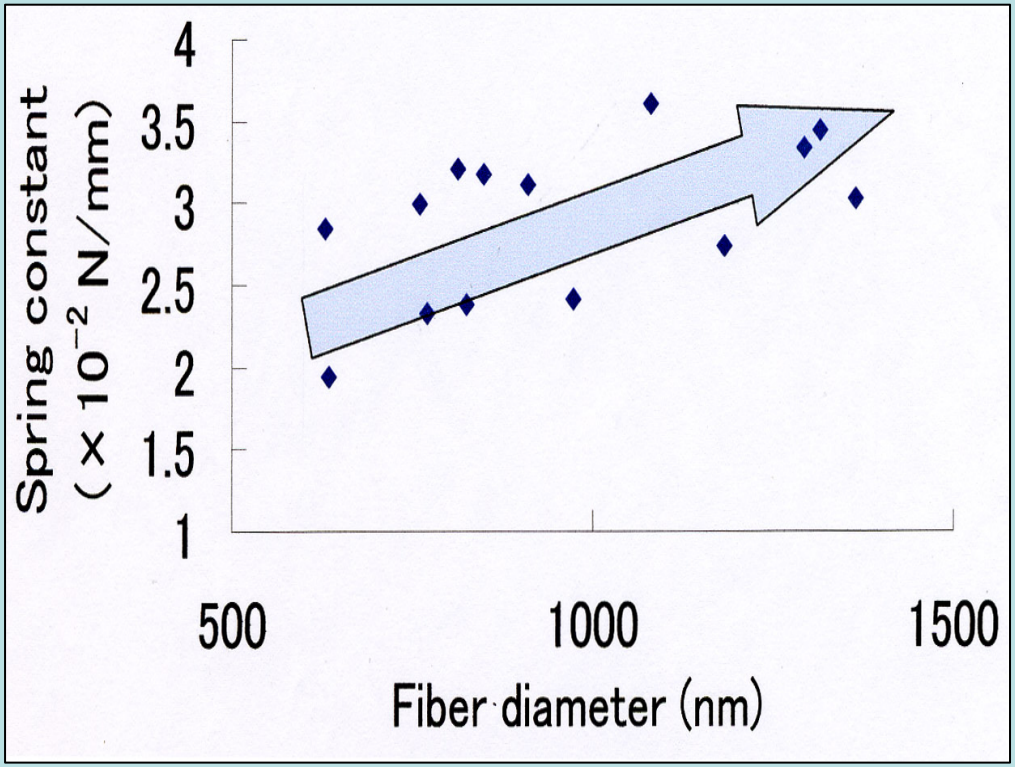


Fig. 2. Temperature dependence of the resistance for the as-grown coil

Influence of coil diameter and fiber diameter on the spring constant of as-grown CMC





Characteristics and Properties of the Carbon Micro-coils

Morphology : Double Helix
- Coil Diameter : 1-10 μm
- Coil Pitch : 0.01-5 μm
- Coil Length : 0.1-10 mm
- Fiber Diameter : 0.01-1 μm

Elasticity (Extension Ratio) : 1.5-10 times

Chemical Composition (wt%) : C=97.5-98.2
H=1.0-1.4
S=0.03-0.09

Crystallographic structure : Amorphous

Density : 1.81-1.88 g/cm

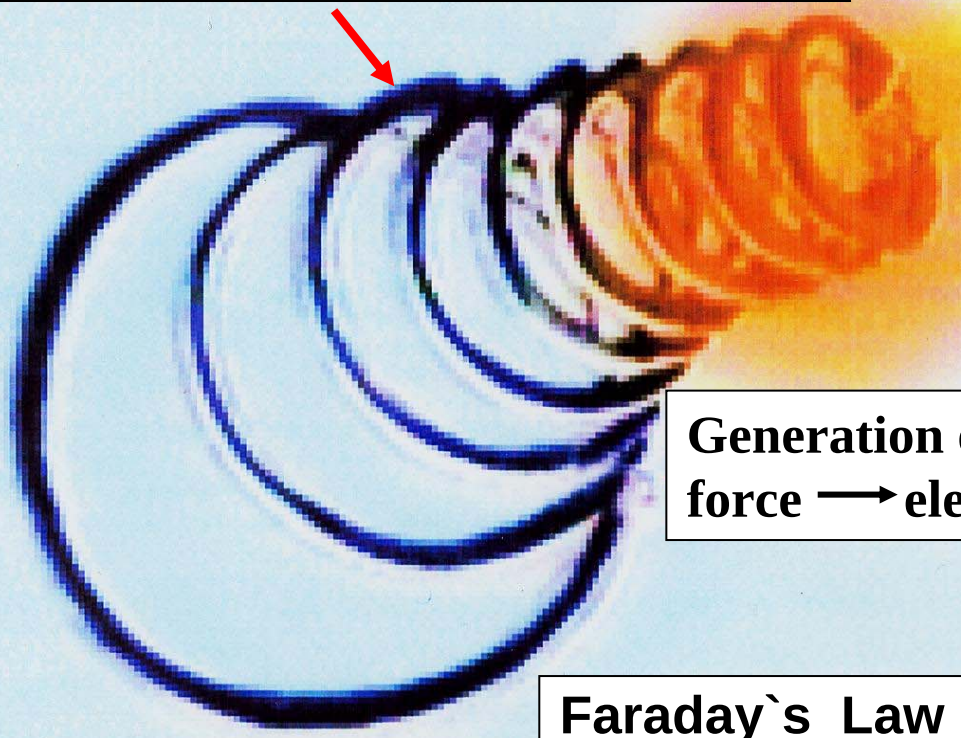
Specific Surface Area : 100-140 m^2/g

Specific Electrical Resistivity : 10-0.1 Ωcm

Thermal Conductivity (Bulk) :
0.0446 W/m/k (for 0.0884 g/cm^3)
0.0562 W/m/k (for 0.2055 g/cm^3)

Interaction of CMC with EM wave

CMC with 3D-Helical/spiral form



Electromagnetic (EM) Wave

Generation of inductive electromotive force → electric current → Joule`s Heat

Faraday`s Law of Electromagnetic Induction

カーボンマイクロコイルに電磁波が当たるとコイル内に誘導起電流が流れジュール熱が発生し熱エネルギーに変わる

Generation of inductive electromotive force

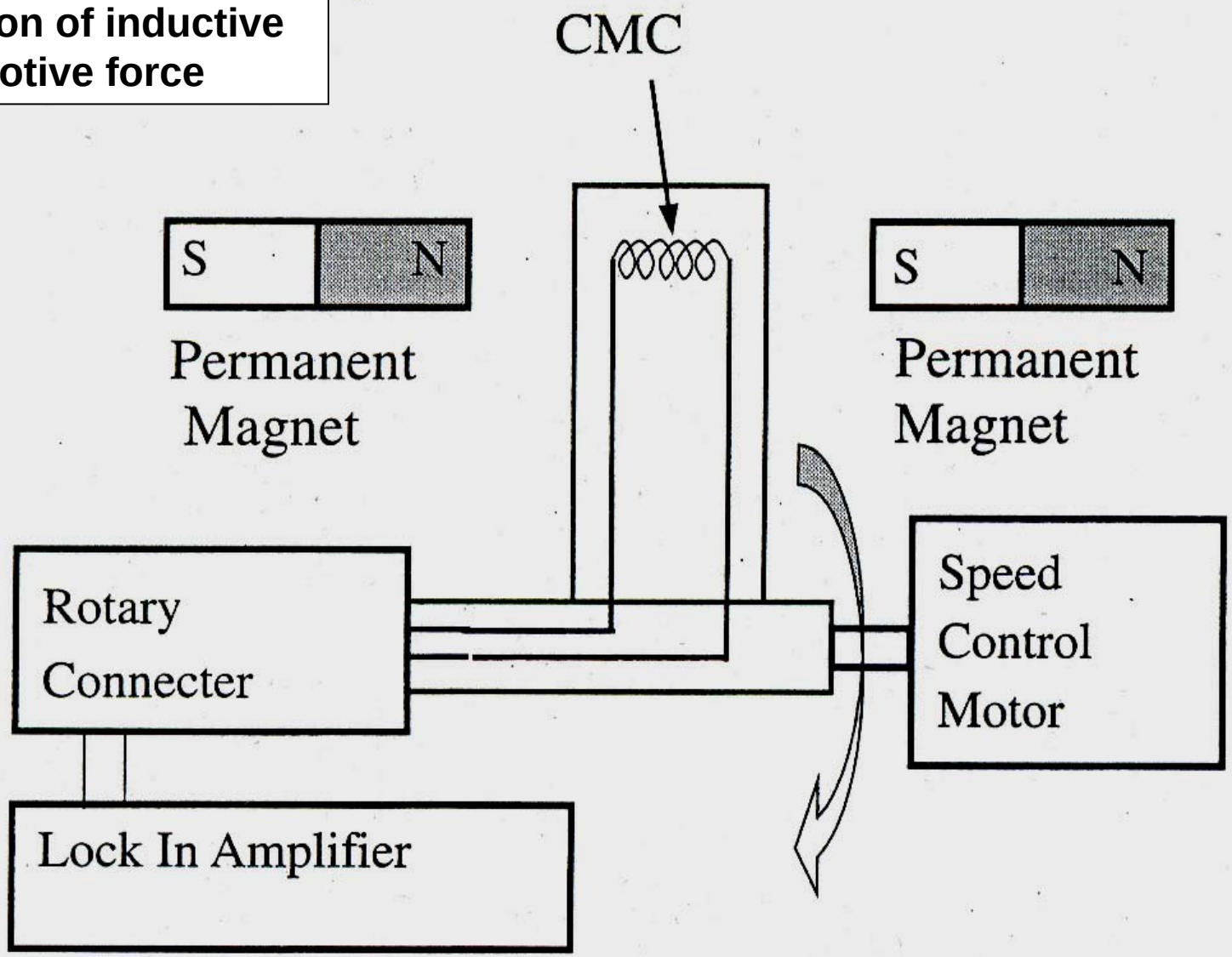


Fig. 2. Schematic of an apparatus used for the measurement of electromagnetic induction of the CMC in a static magnetic field.

Generation of inductive electromotive force

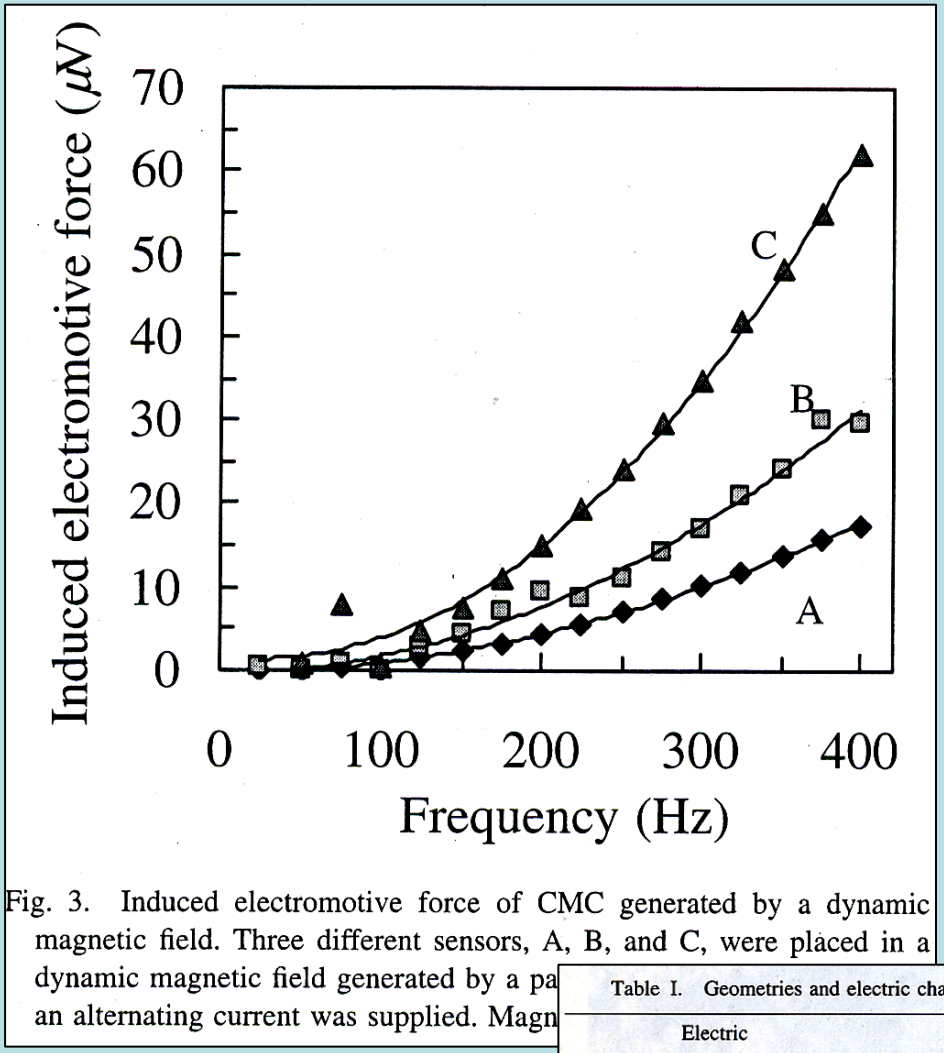


Fig. 3. Induced electromotive force of CMC generated by a dynamic magnetic field. Three different sensors, A, B, and C, were placed in a dynamic magnetic field generated by a pa
an alternating current was supplied. Magn

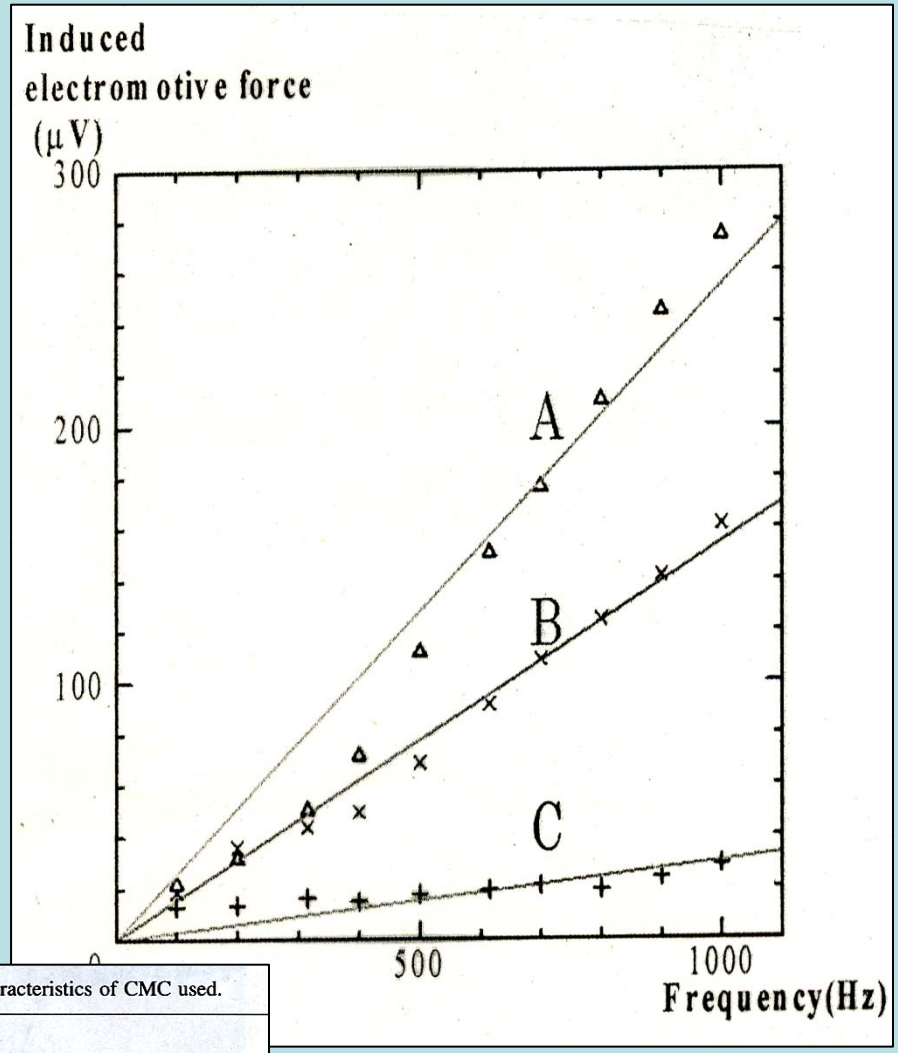
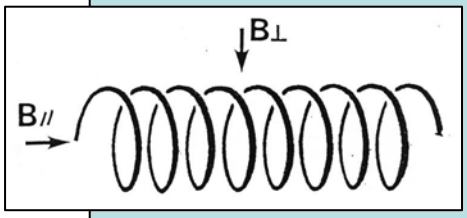
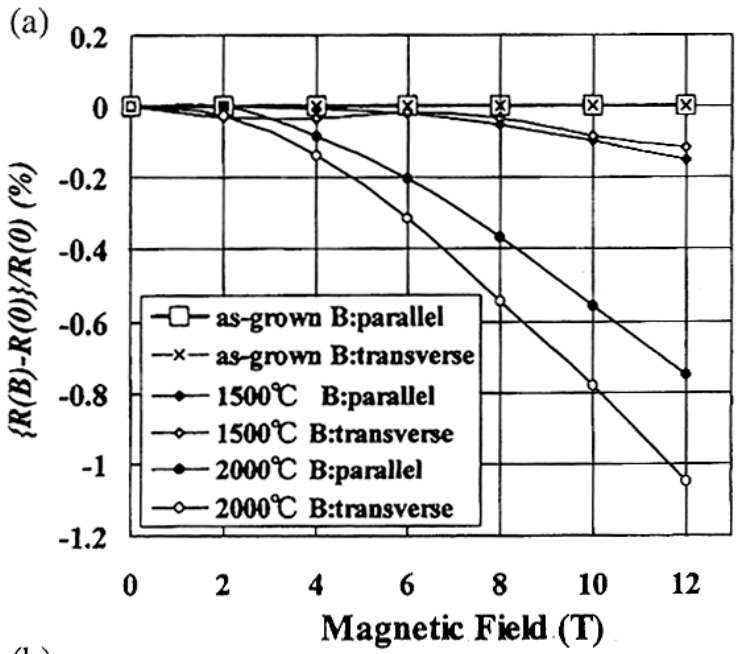


Table I. Geometries and electric characteristics of CMC used.

Sensor No.	Electric resistance (kΩ)	Length (μm)	No. of Turns	Diameter (μm)	Resistivity (10^{-6} kΩ·m)
A	273	568	132	4	6.04
B	353	1114	202	5	6.22
C	1090	2300	534	4	5.96

Application to magnetic sensor element





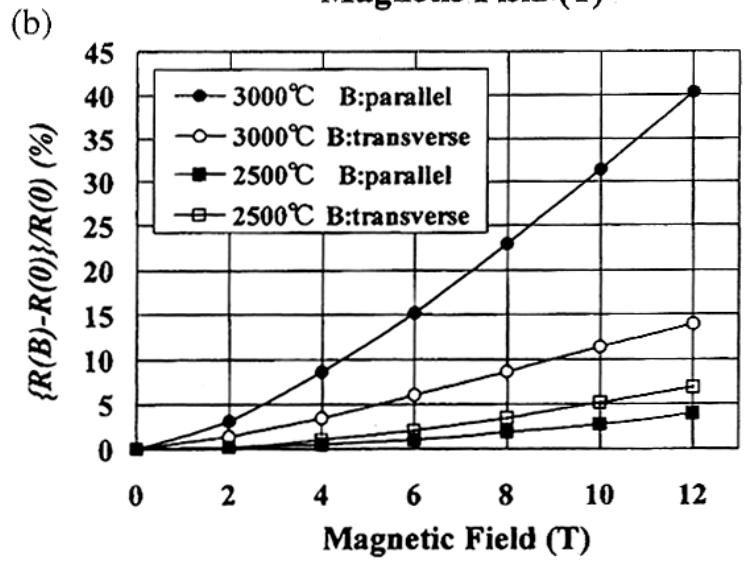
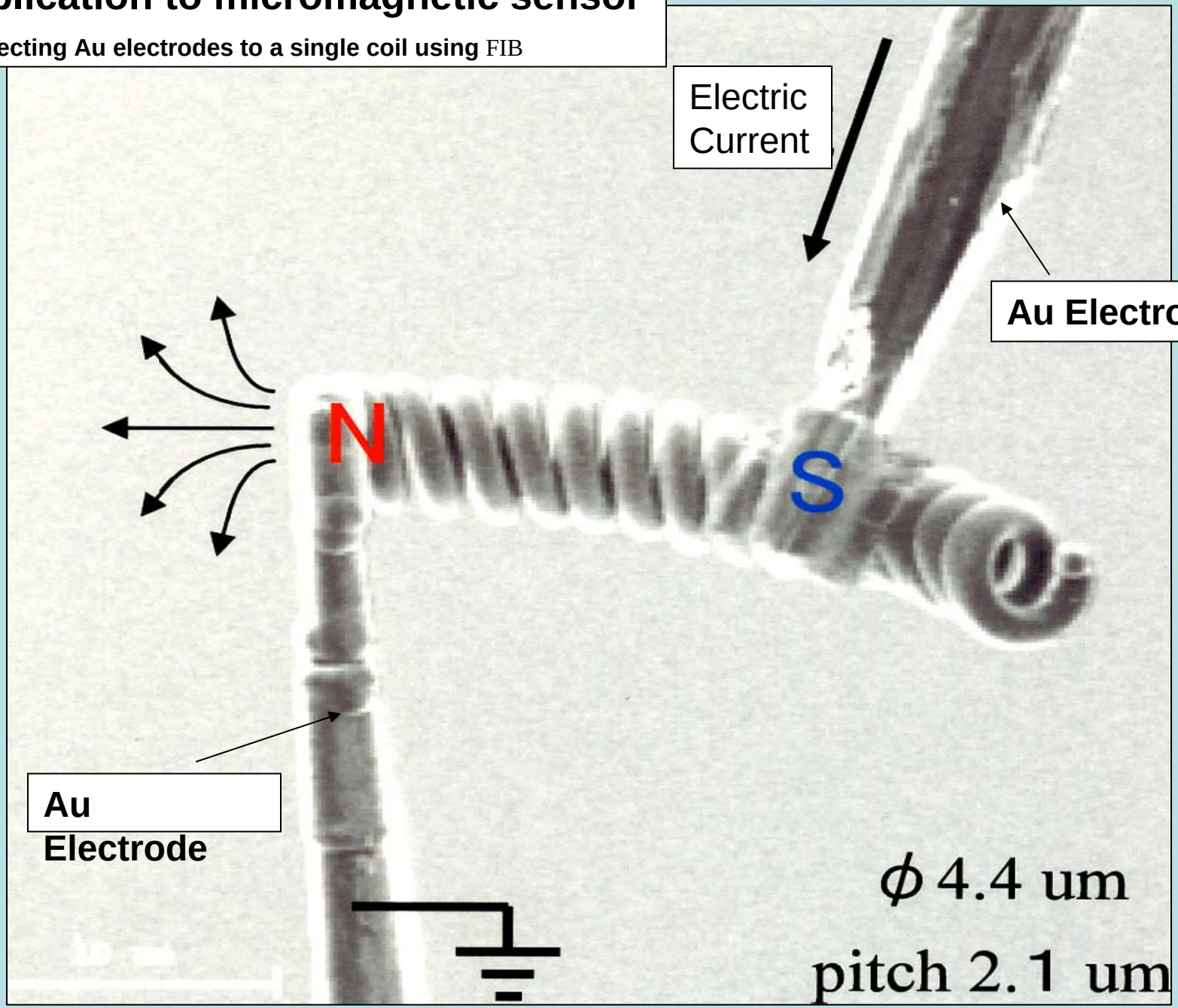


Fig. 5. Field direction dependence of magnetoresistance measured at 300 K (a) for the as-grown coil and the coils annealed at 1500 and 2000 °C, and (b) for the coils annealed at 2500 and 3000 °C.

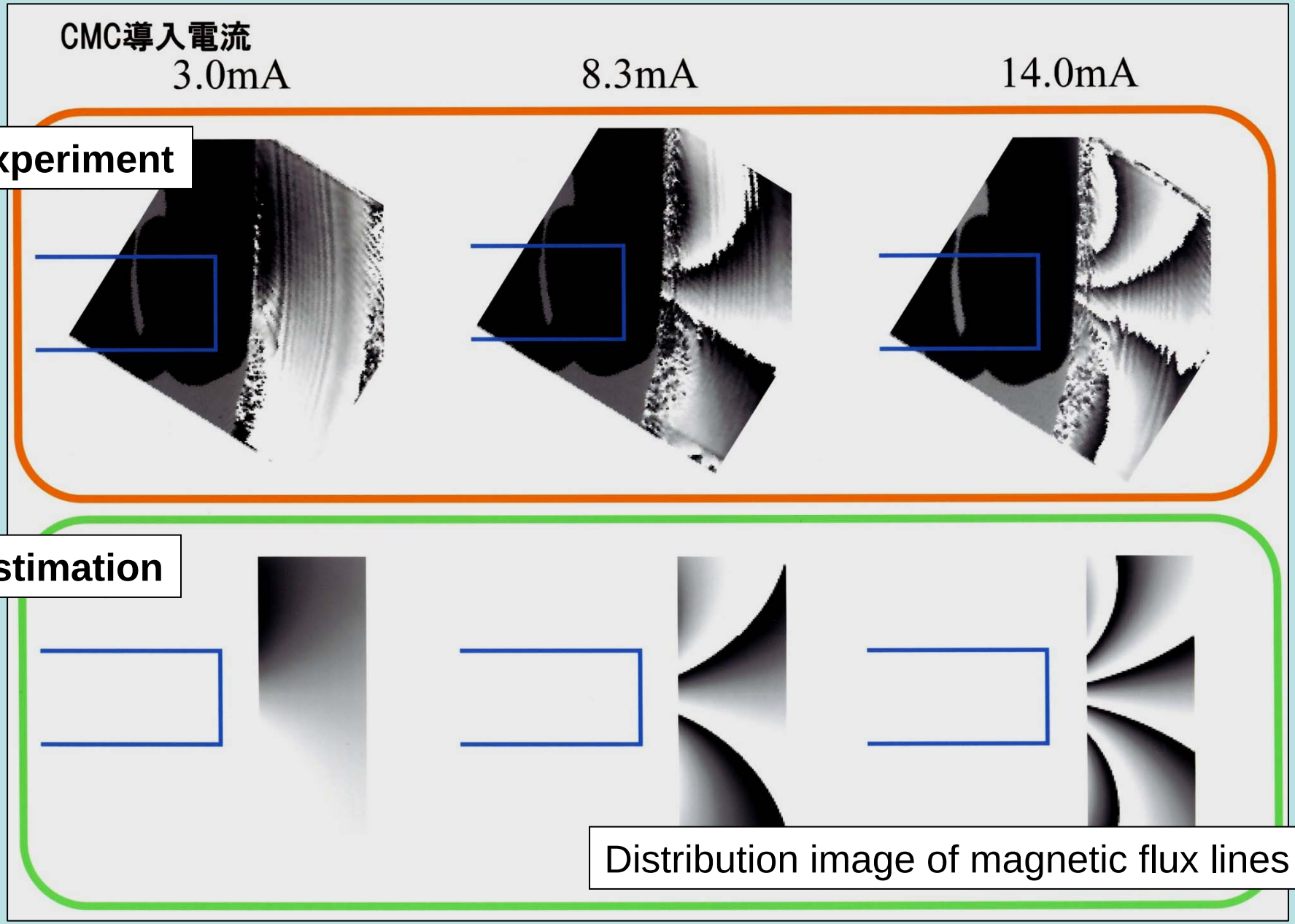
Relationship between magneto-resistance and magnetic field of a piece of CMC.

Application to micromagnetic sensor

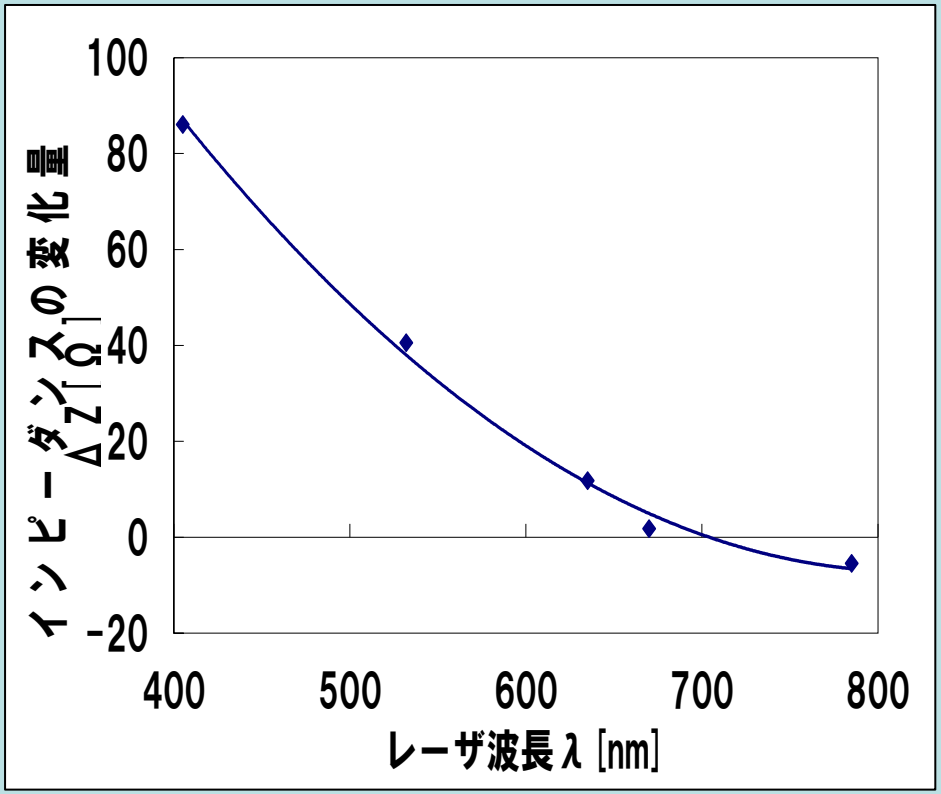
Connecting Au electrodes to a single coil using FIB



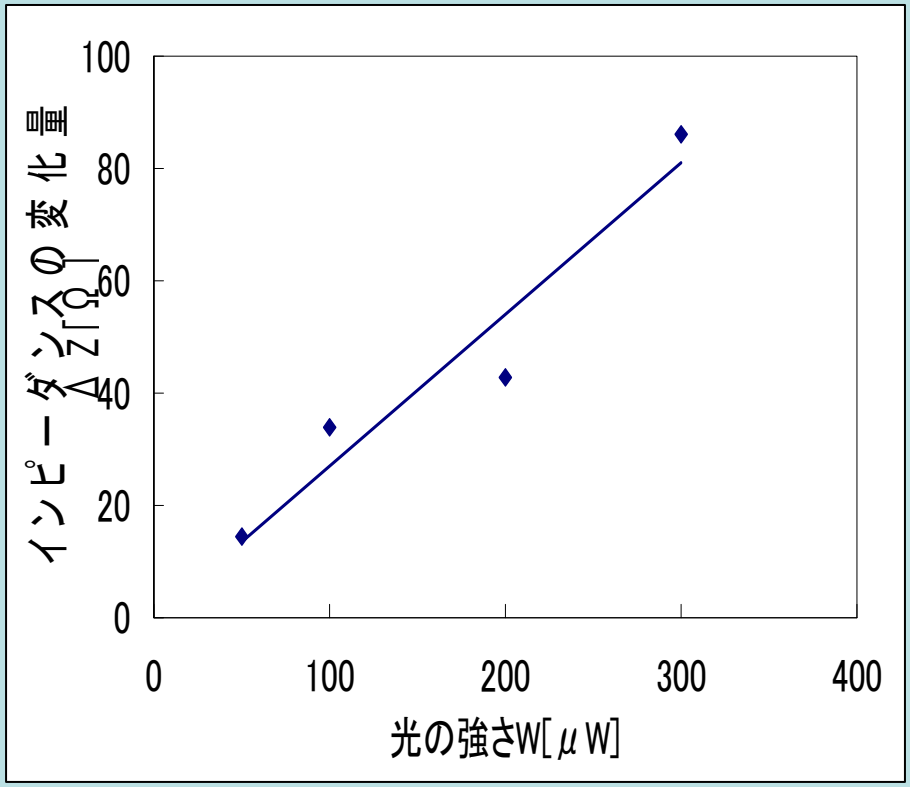
Visualization of magnetic flux by en Electron pholograph



Application to laser sensor

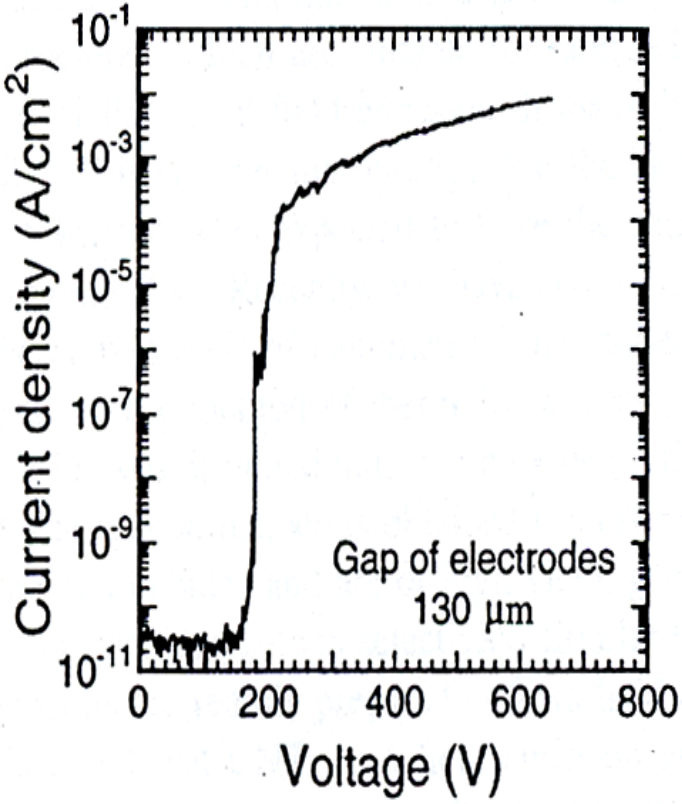


Relationship between wavelength of laser and impedance of a piece of CMC.
(Measured frequency=1kHz、Laser power=300μW)



Relationship between laser power and impedance of a piece of CMC.
(f=1kHz、λ=405nm)

Application to field emitter



ig. 4. Curve of the emission current density vs applied voltage for a typical nanocoil field emitter. The low turn-on voltage and high current density are obtained.

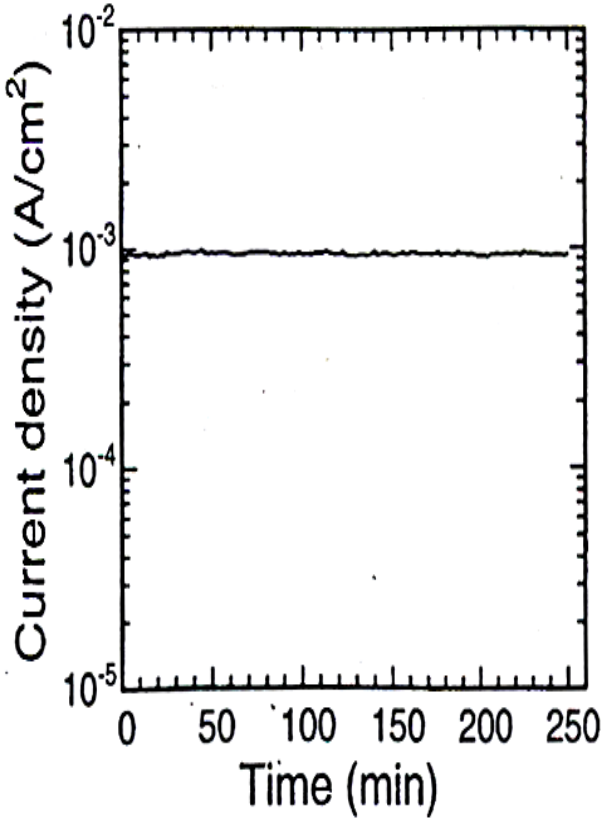
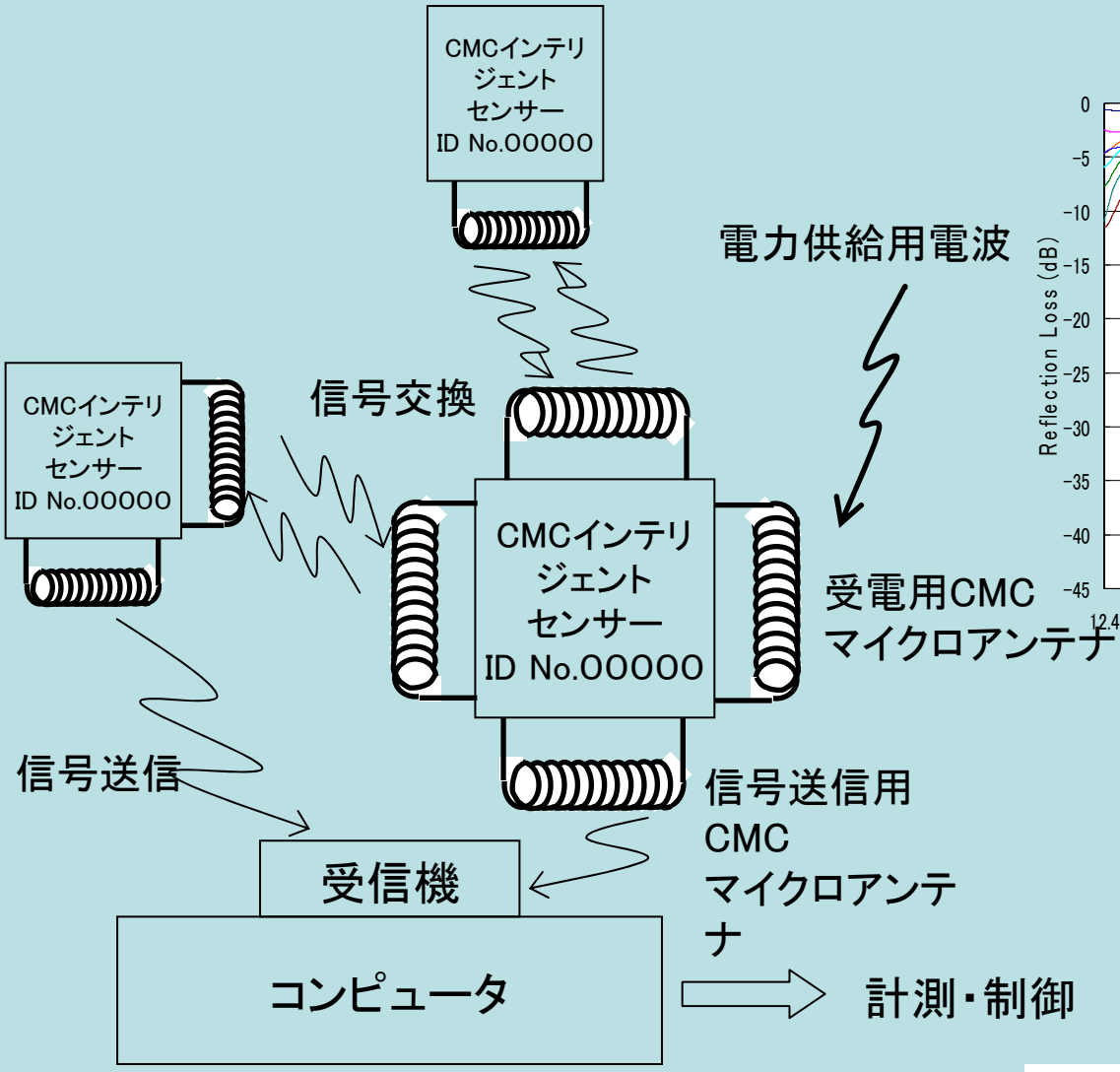
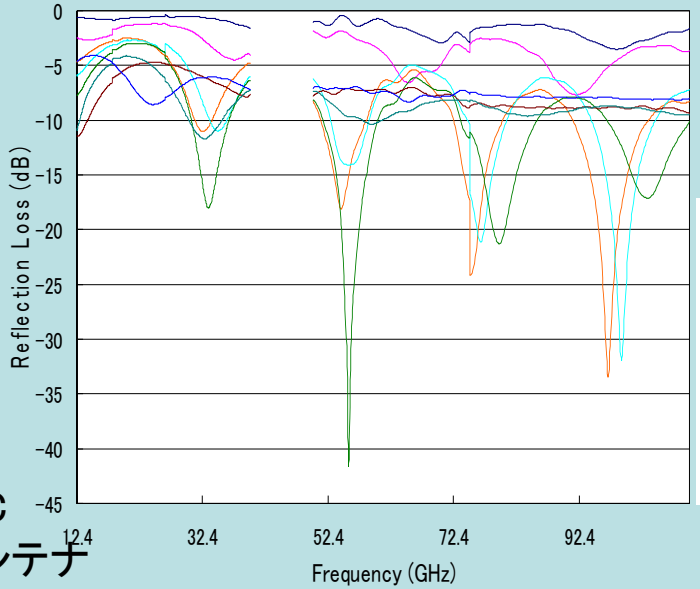


Fig. 5. Stability test of the carbon nanocoil field emitter. The current density is very stable near 1 mA/cm^2 for 250 min without diminution.

ワイヤレス独立機能型CMCインテリジェントセンサー（イメージ図）

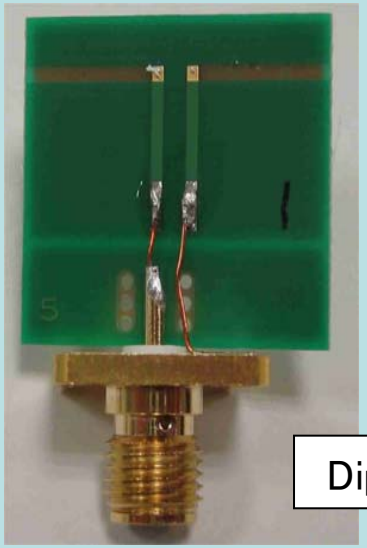


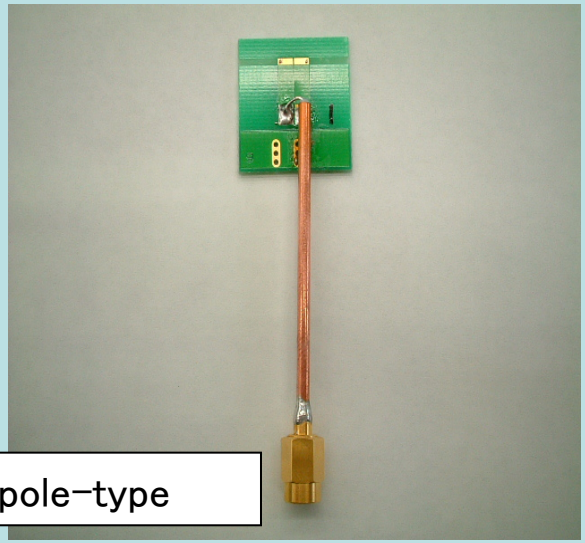
CMCの電磁波吸収特性



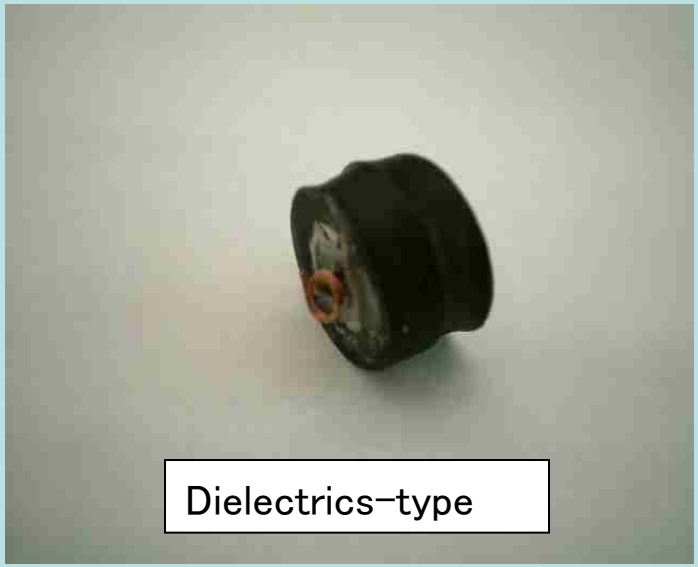
Potential application in micro antenna

Micro antenna of various types are prepared.

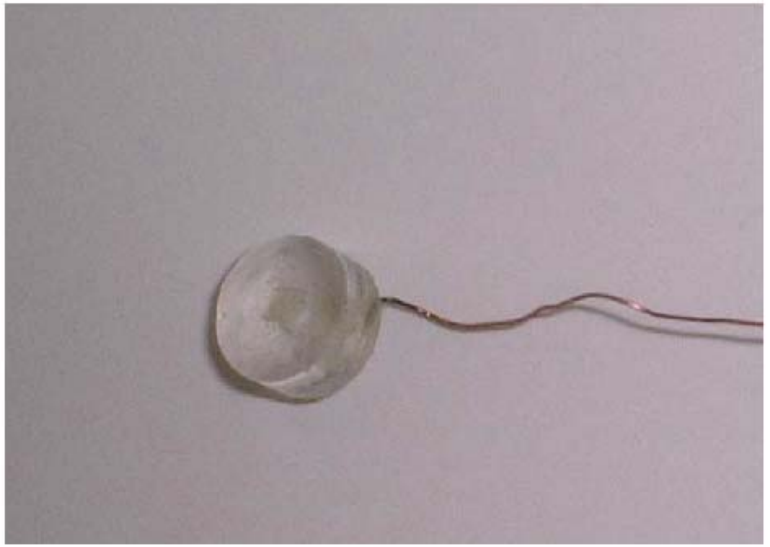




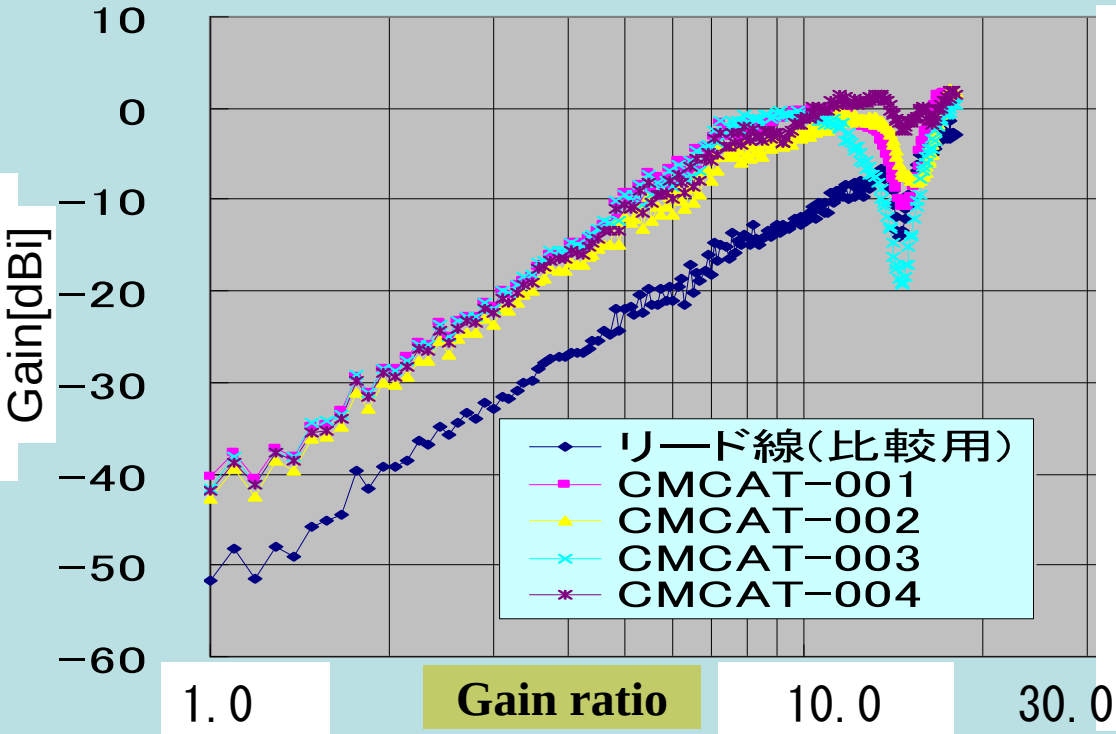
Dipole-type



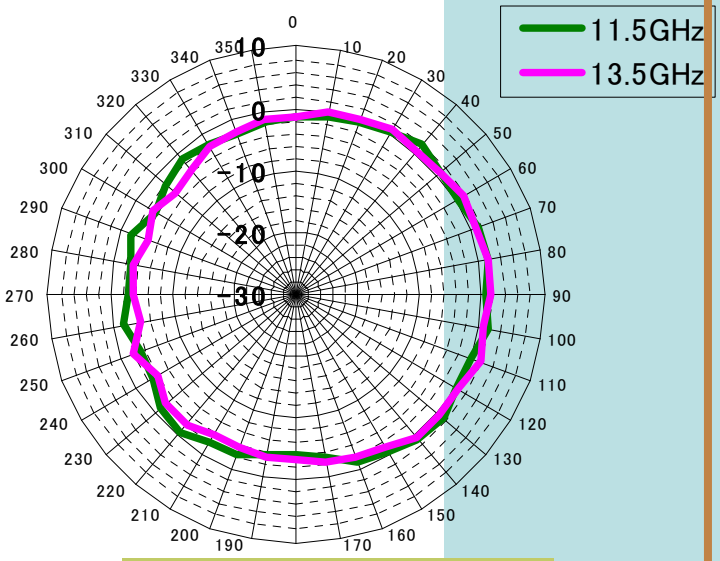
Dielectrics-type



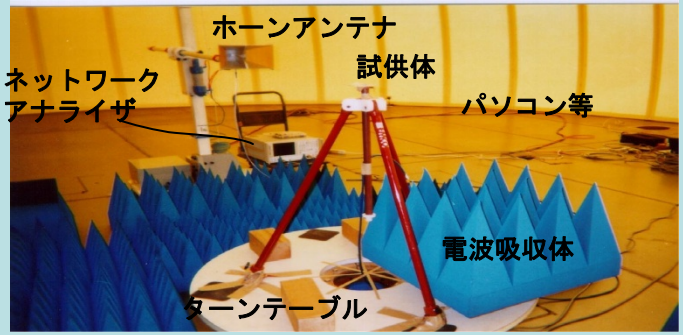
Characteristics of micro-antenna for space development



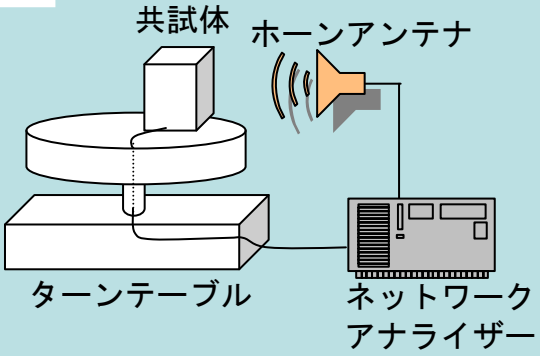
Gain ratio



Radiation pattern



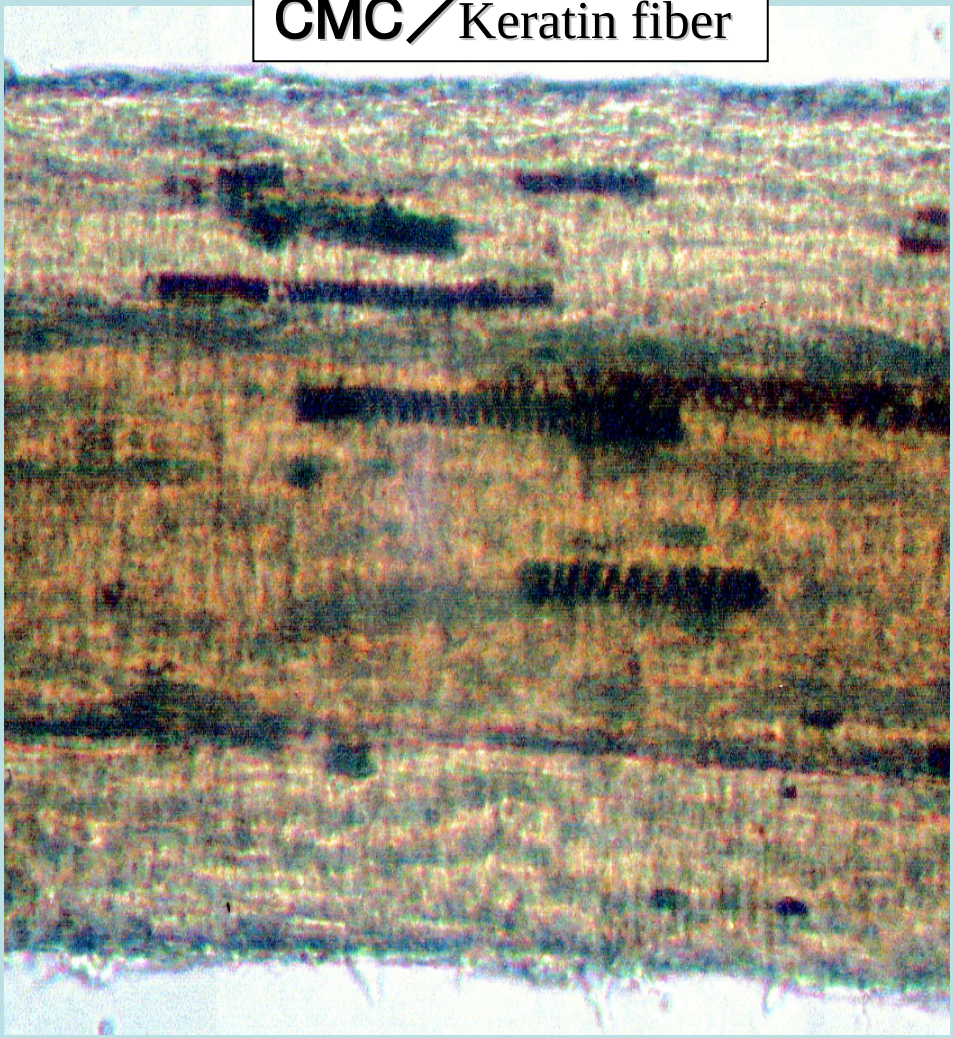
Measurement/evaluation system



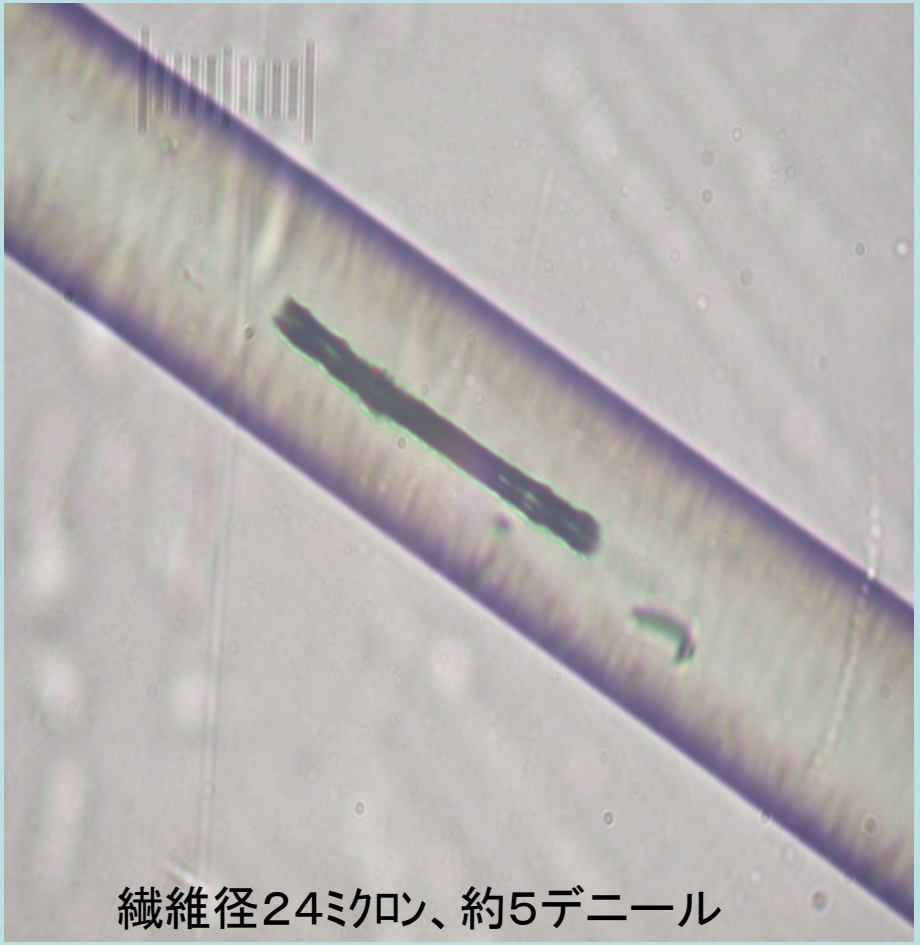
CMC Technology Development Co., Ltd.

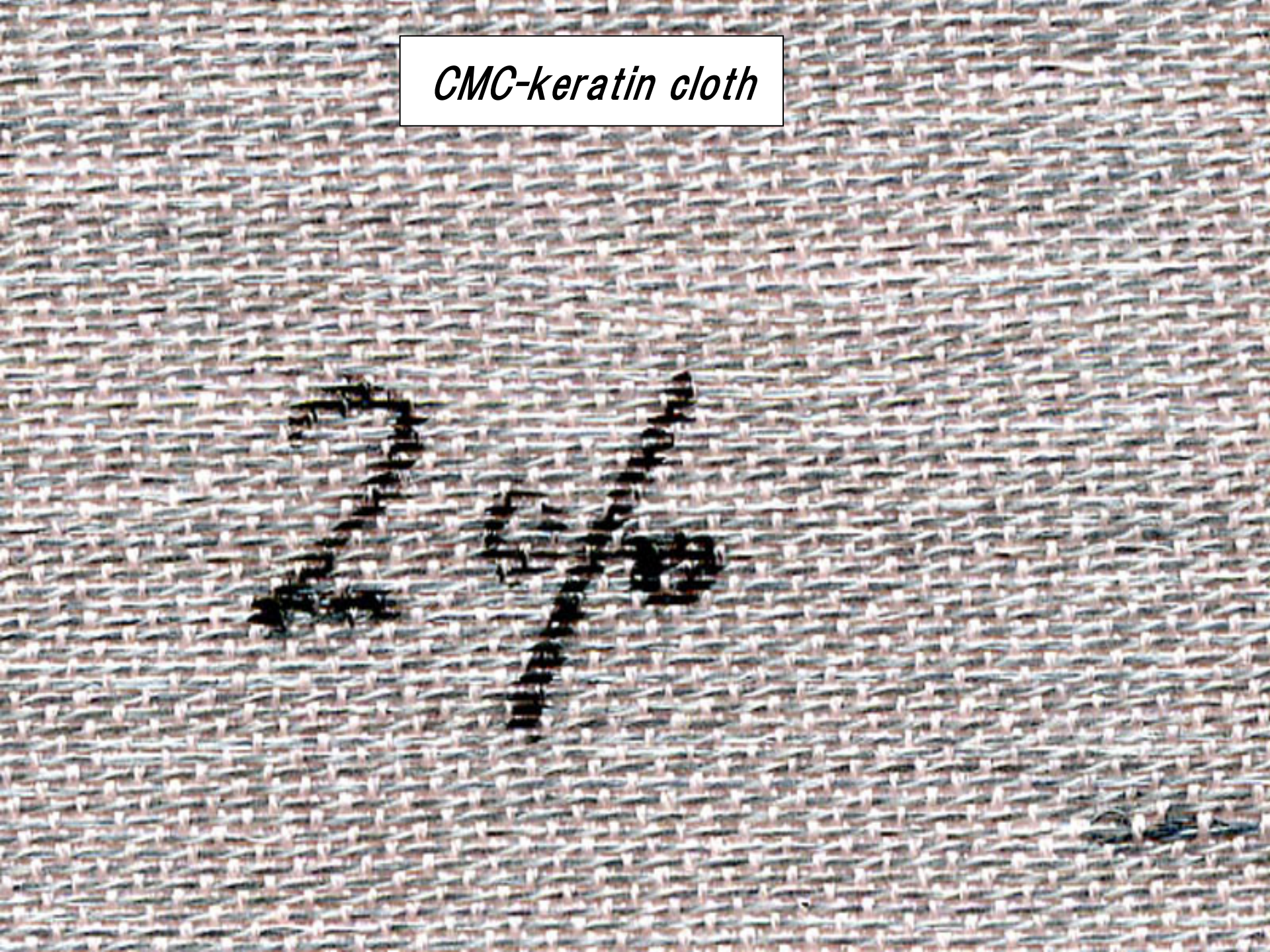
CMC-Containing Fibers

CMC／Keratin fiber

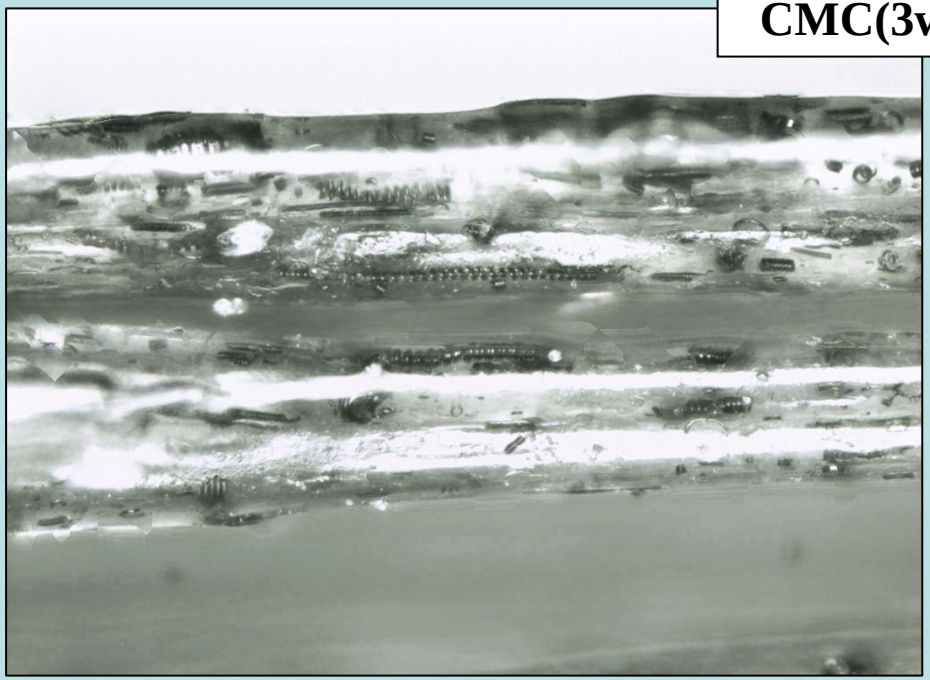


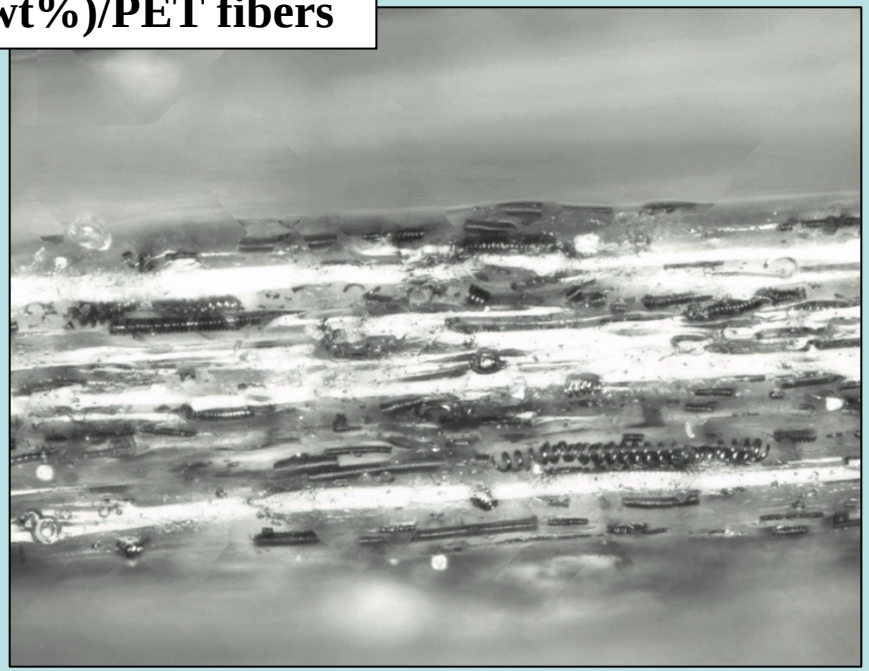
CMC／PLA Fiber

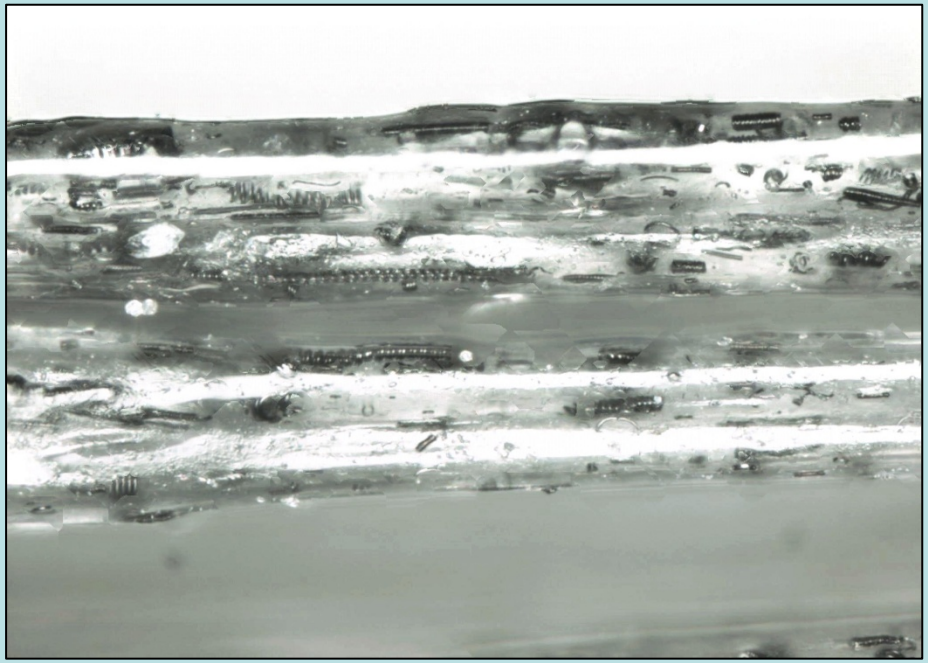


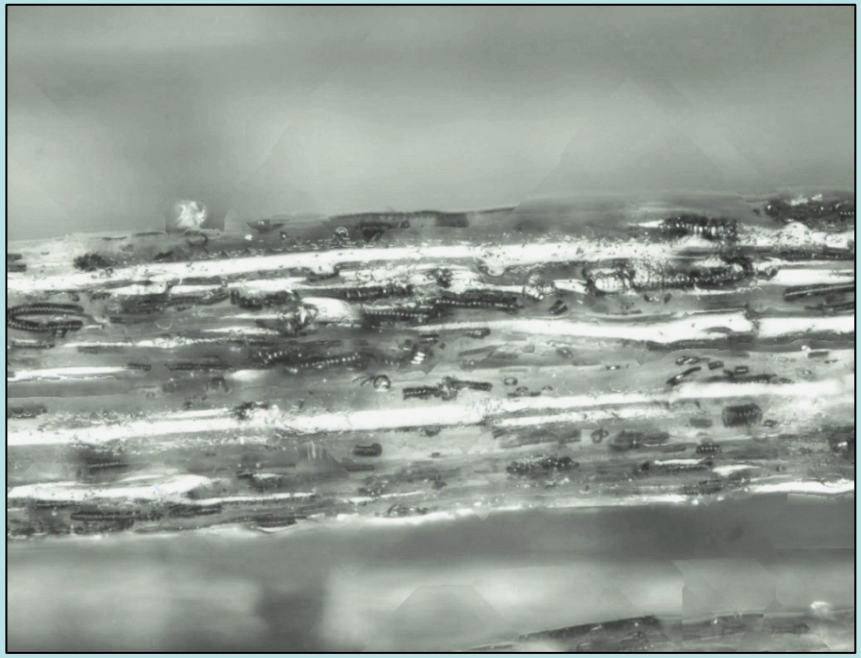

CMC-keratin cloth

CMC(3wt%)/PET fibers



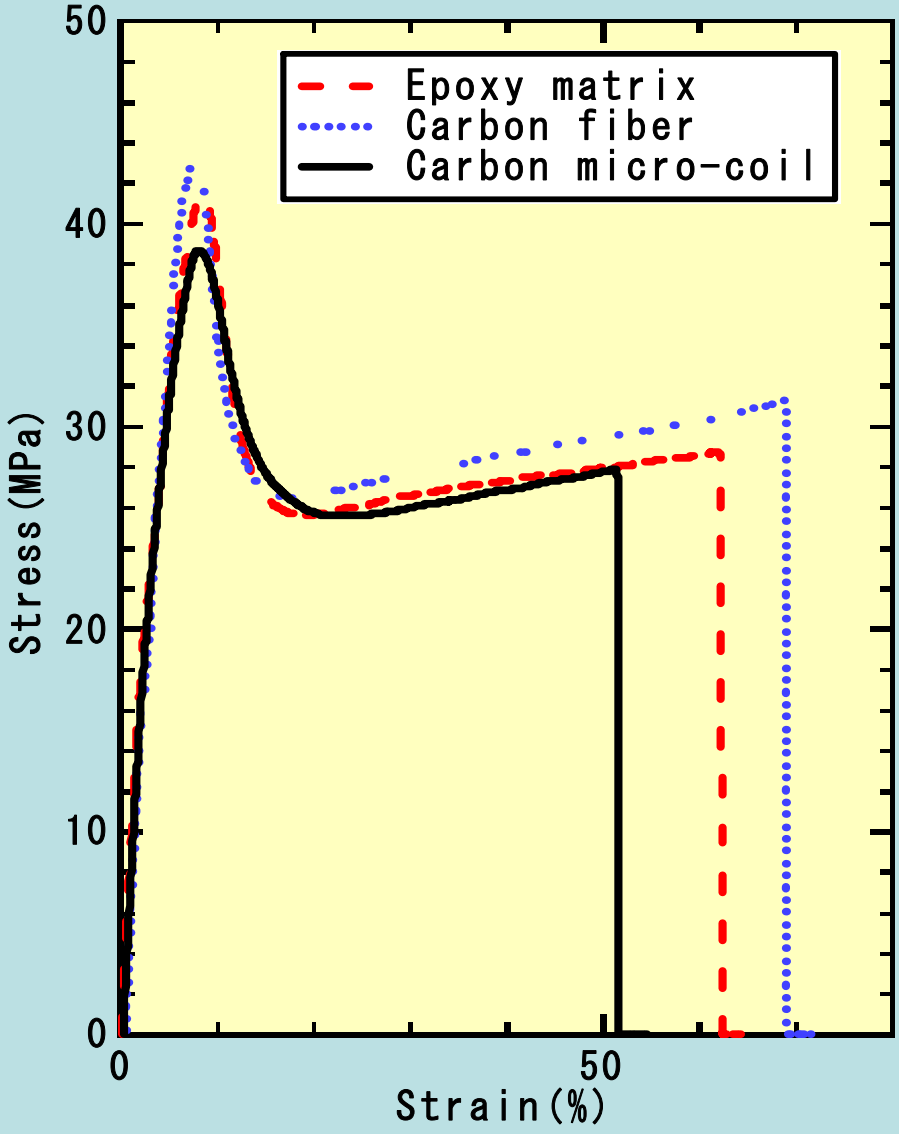






Characteristics of CMC as reinforcing fibers

Stress-strain diagram of CMC/Epoxy resin（Young's modulus:700MPa）composite



	Tensile strength (MPa)	Stretch (%)	Young's modulus (MPa)
Blank	42	65	690
Carbon fiber (3wt%)	44	67	750
CMC 3wt%	40	51	720

(n=3)

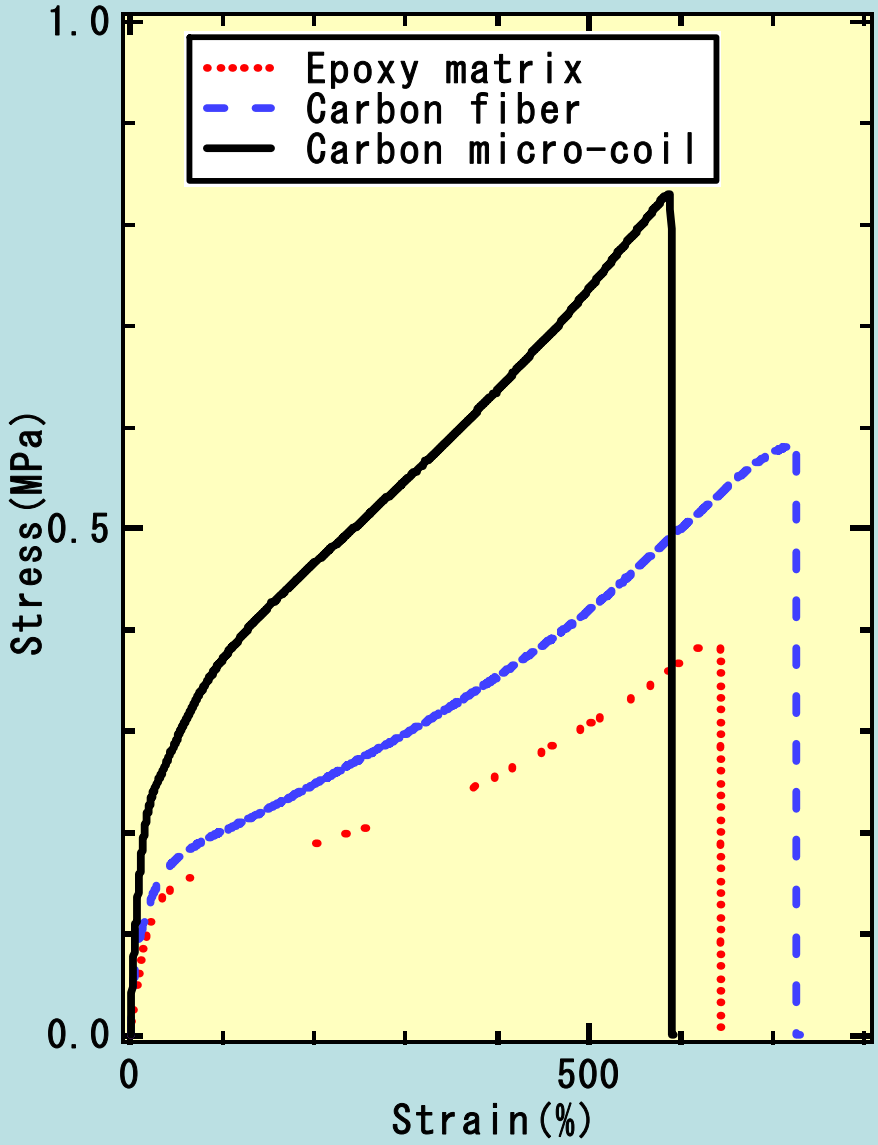
Straight carbon fiber composite

Tensile strength, Stretch and Young's modulus: slightly increased

CMC composite

- **Tensile strength：slightly decreased**
- **Stretch, Young's modulus: slightly increased**

Stress-strain diagram of CMC/Epoxy resin（Young's modulus:1MPa）composite



	Tensile strength (MPa)	Stretch (%)	Young's modulus (MPa)
Blank	0.36 (σ=0.035)	614 (σ=36)	1.2 (σ=0.12)
Carbon fiber (3wt%)	0.56 (σ=0.031)	714 (σ=61)	1.4 (σ=0.13)
CMC (3wt%)	0.83 (σ=0.034)	605 (σ=16)	2.1 (σ=0.37)

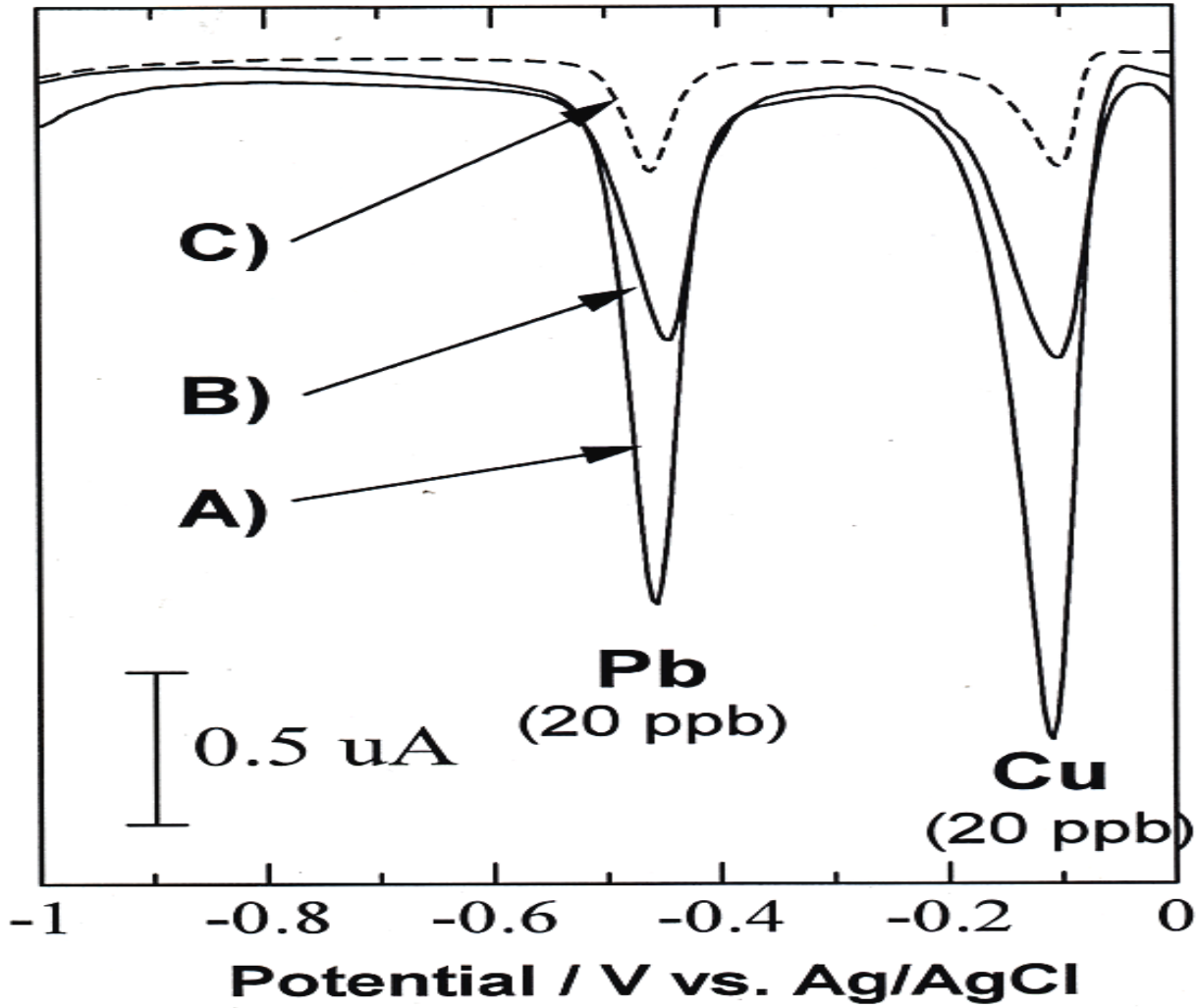
Straight carbon fiber composite

Tensile strength, extension and Young's modulus: slightly increased

CMC composite

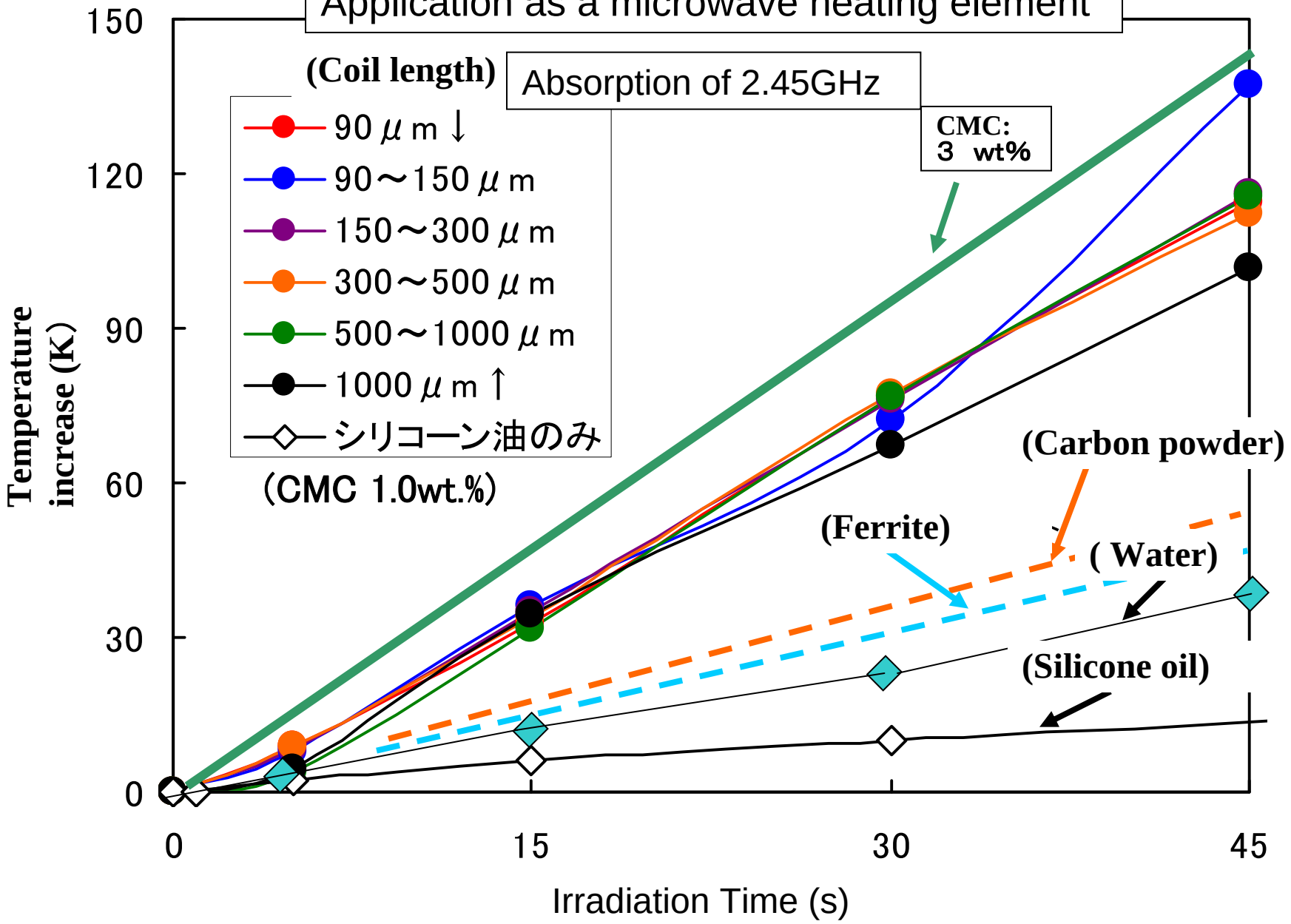
Tensile strength, Young's modulus: increased by ca. 2 times

Application to analytical microsensor



Square wave stripping voltammograms of 20 ppb Cu(II) and Pb(II) at (A) CMC (heat treated), (B) CMC (as grown) and (C) graphite electrodes.
Electrolyte:0.1 M HCl

Application as a microwave heating element

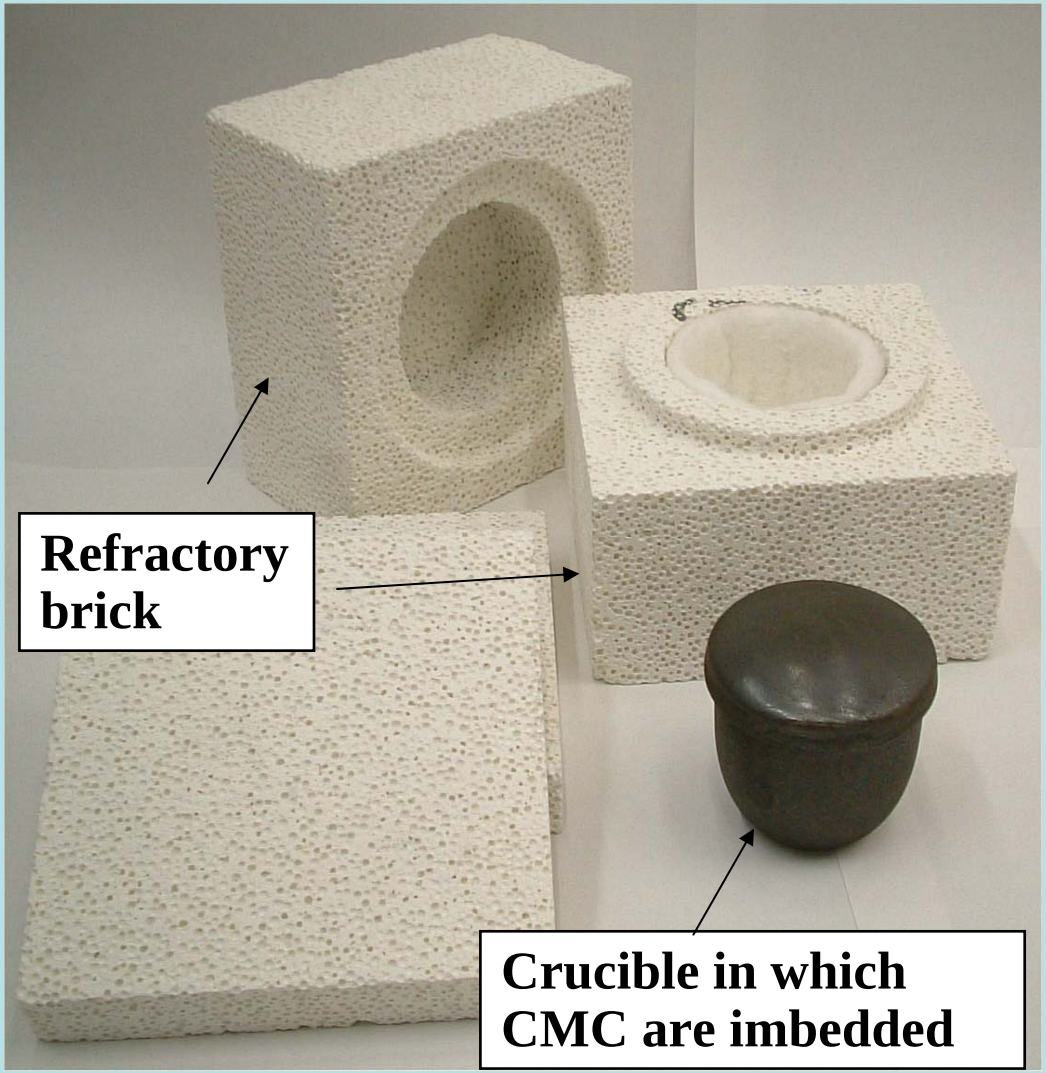


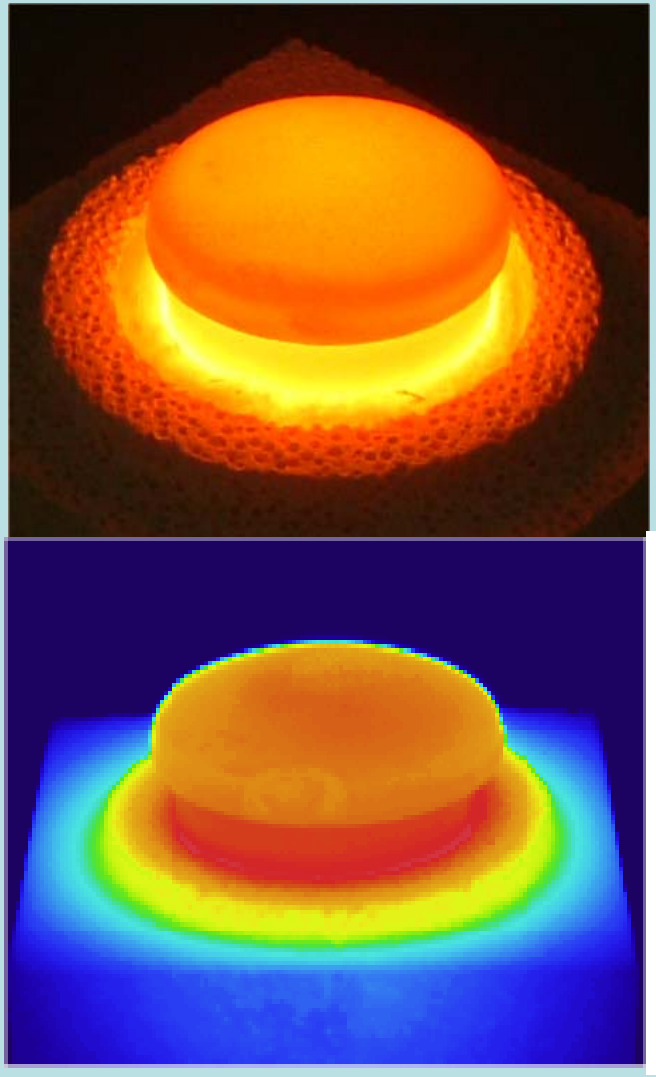
Temperature increase of CMC(1wt%)/silicone oil by microwave oven heating

CMC試料の温度上昇

“Electron Crucible” heated by a microwave oven for ca. 15 min

IR Thermograph



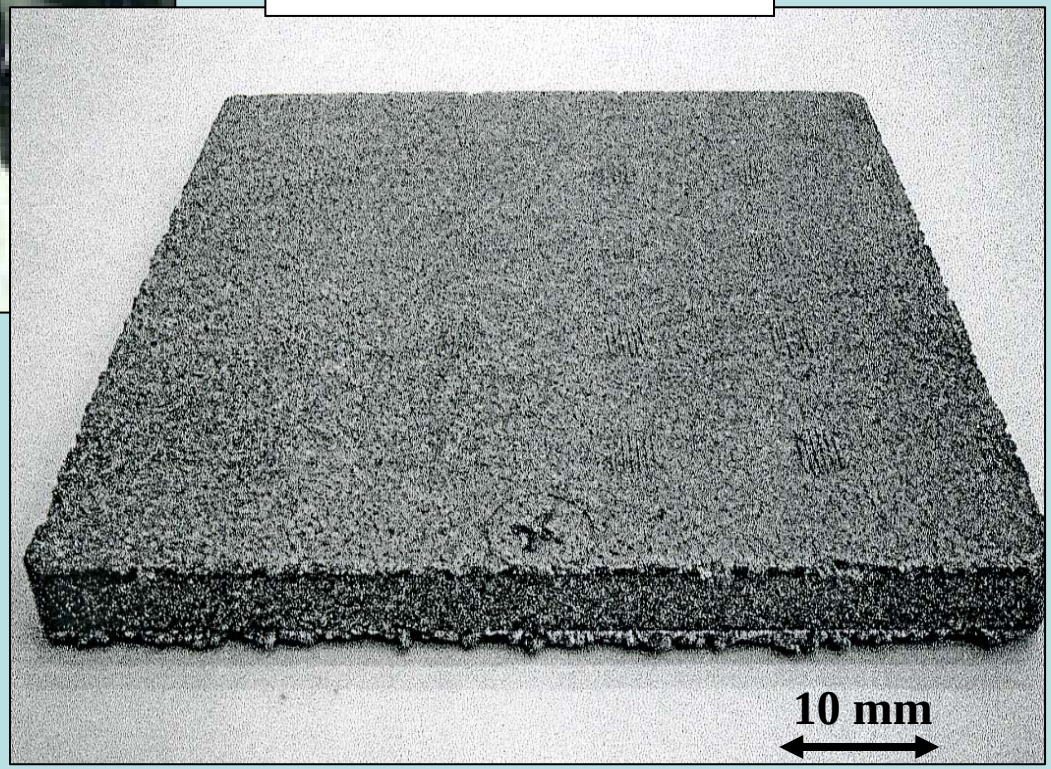


High microwave absorption property of CMC is now applied in a microwave oven crucible. That is, the CMC was embedded into ceramic crucible, and the crucible was heated for 10 min in microwave oven. The highest temperature was attained up to 1200℃

Commercially available representative CMC (powder-like forms)

CMC(1wt%)/PMMA Bead

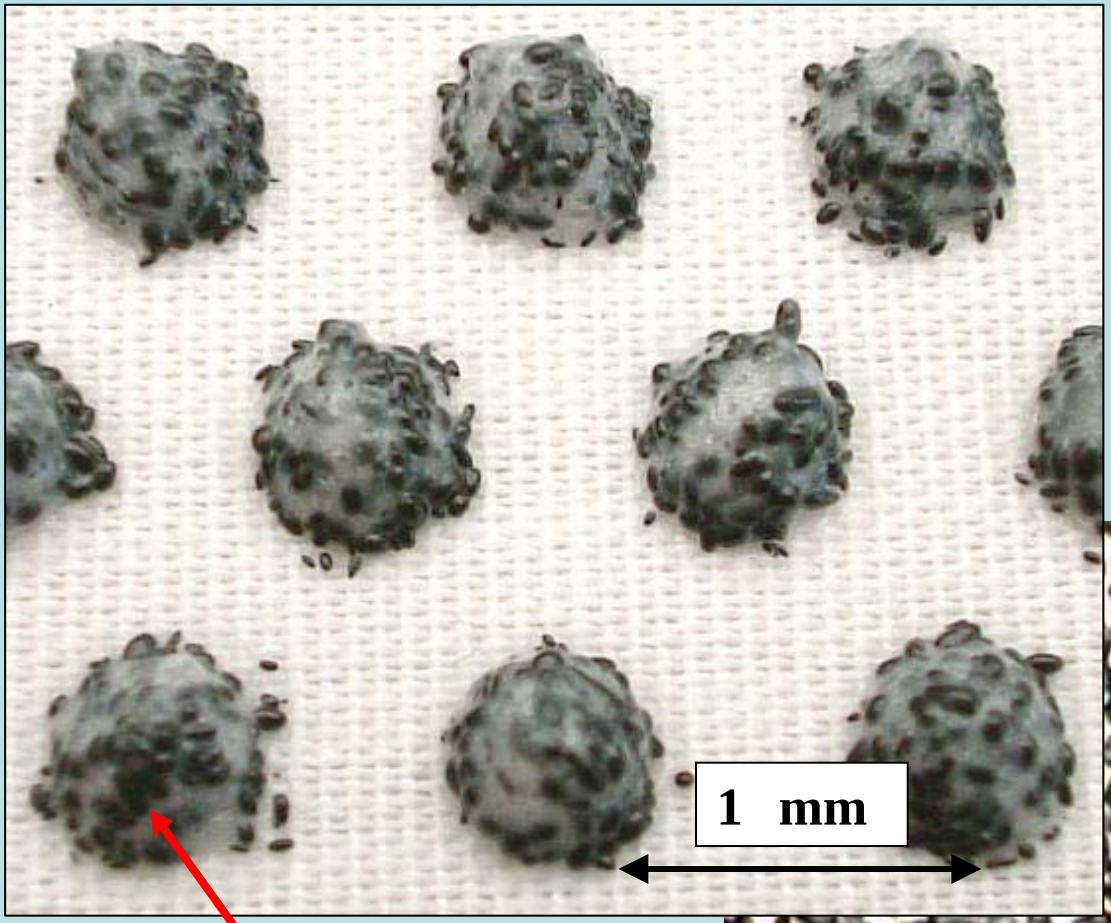
CMC/PMMA Foam



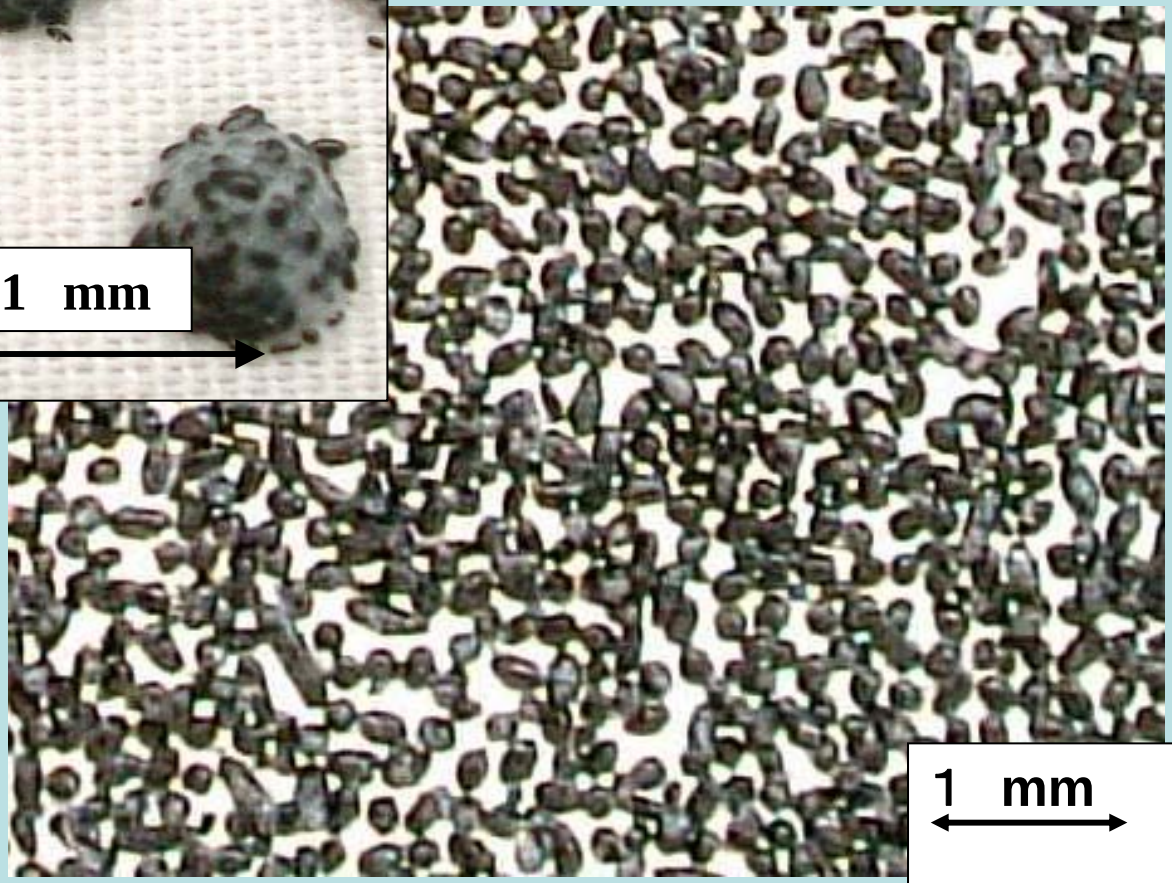
These are CMC and PMMA composite beads and foams.

Visualization screen of electromagnetic field

Microwave（2.45GHz, λ =12 cm）



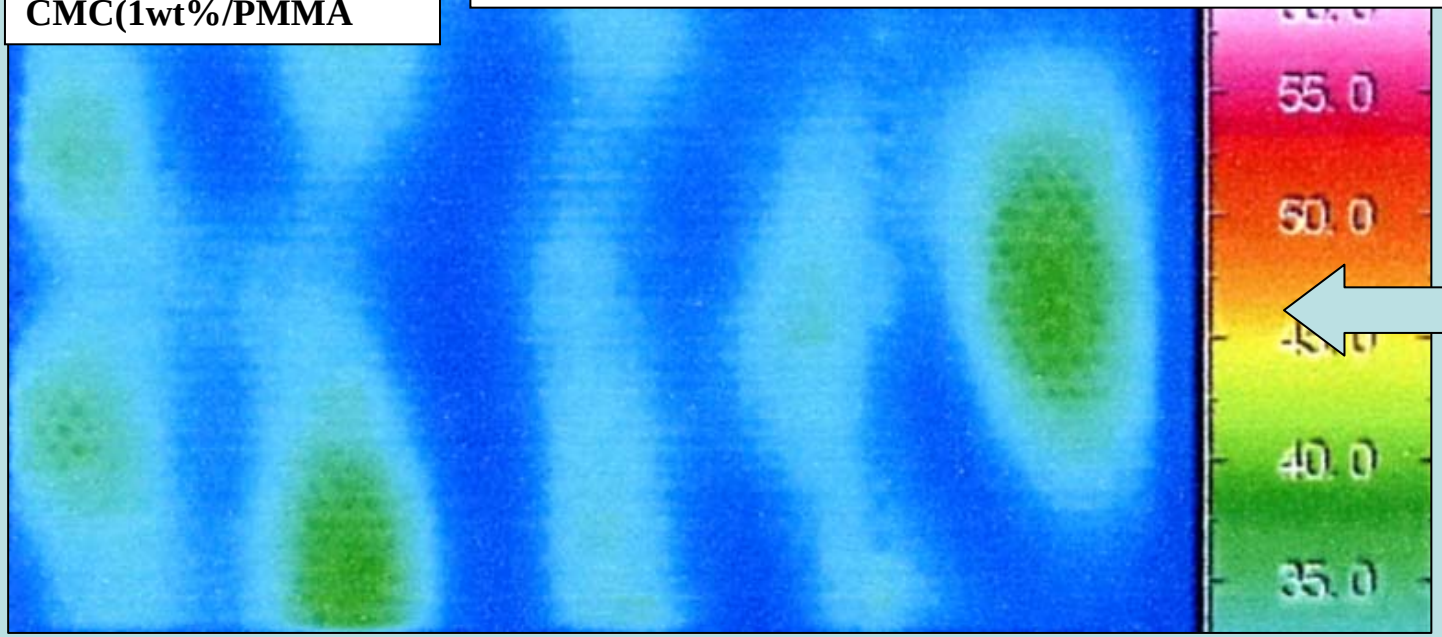
CMC/PMMA bead



This is a microwave visualization panel which was formed by the CMC/PMMA beads and was vertically set in the central part of a microwave oven, and the formed heat was visualized by an IR thermograph.

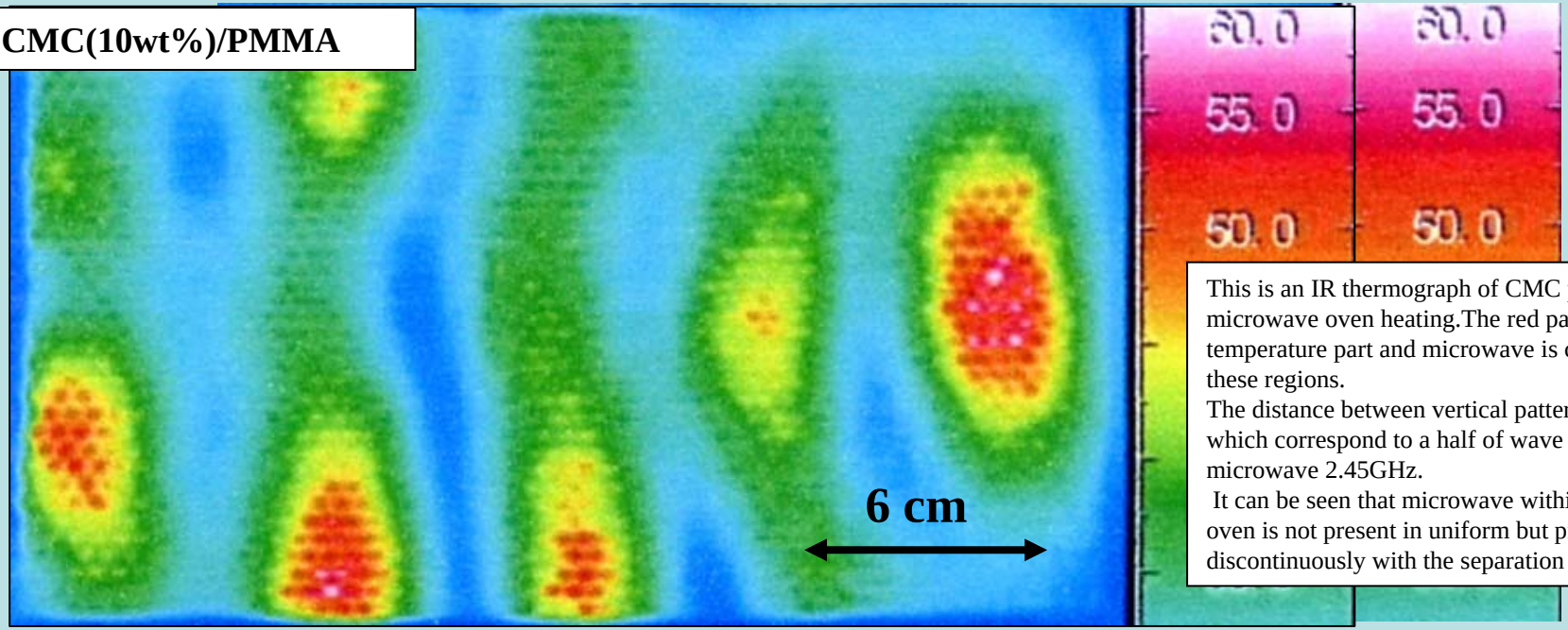
Visualization of microwave （2.45GHz)

CMC(1wt%/PMMA



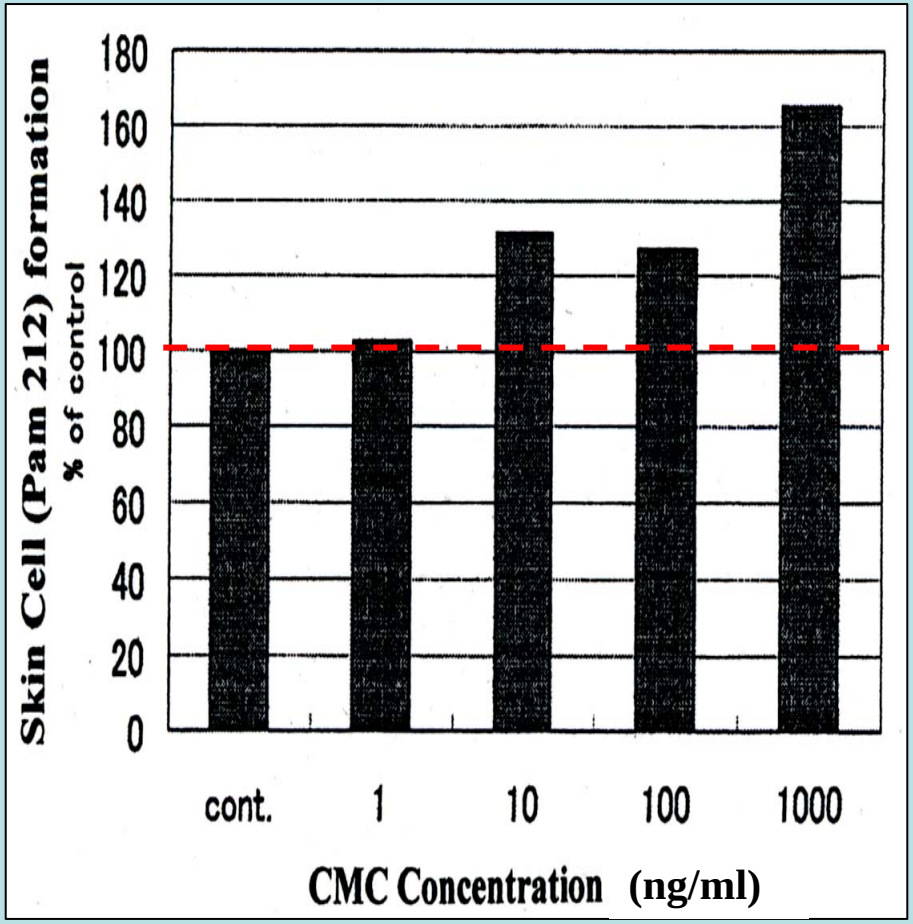
Microwave

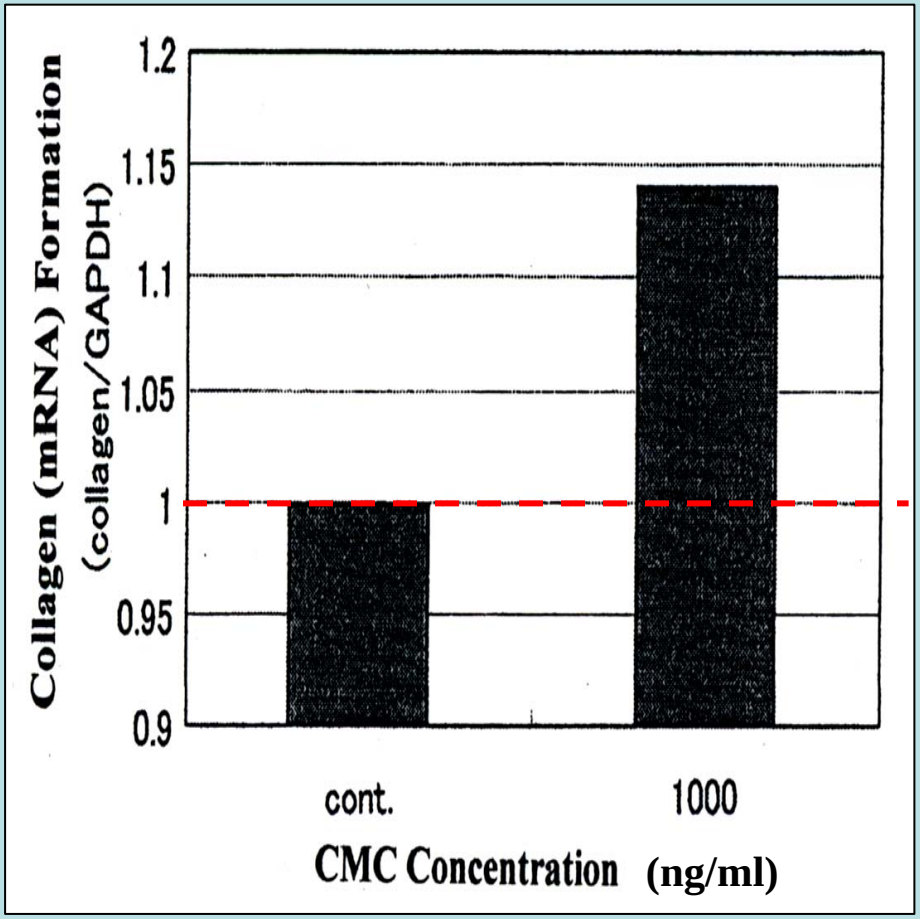
CMC(10wt%)/PMMA



This is an IR thermograph of CMC panel after microwave oven heating.The red part is a high temperature part and microwave is concentrated in these regions.
The distance between vertical patterns is about 6 cm, which correspond to a half of wave length 12 cm of microwave 2.45GHz.
It can be seen that microwave within a microwave oven is not present in uniform but present discontinuously with the separation of 6 cm.

Application to cosmetics





Breeding effects of CMC on skin cells and collagen fibrils

This figure shows the effect of CMCs on the skin cell and collagens breeding. It can be seen that the number of skin cell; Pam 212,increases by 160% by the addition of CMC of 1000ng/ml、against a control sample, that is, without addition of CMC. In the case of collagen fibrous too, breeding effect of the addition of CMC was observed.

fg

MENARD
fairgrace

essence pact

This is the most graceful day in my life.

CMC is also now applied to cosmetics as shown in this micrograph.
Very small amount of CMC is added to compact cosmetic powders.

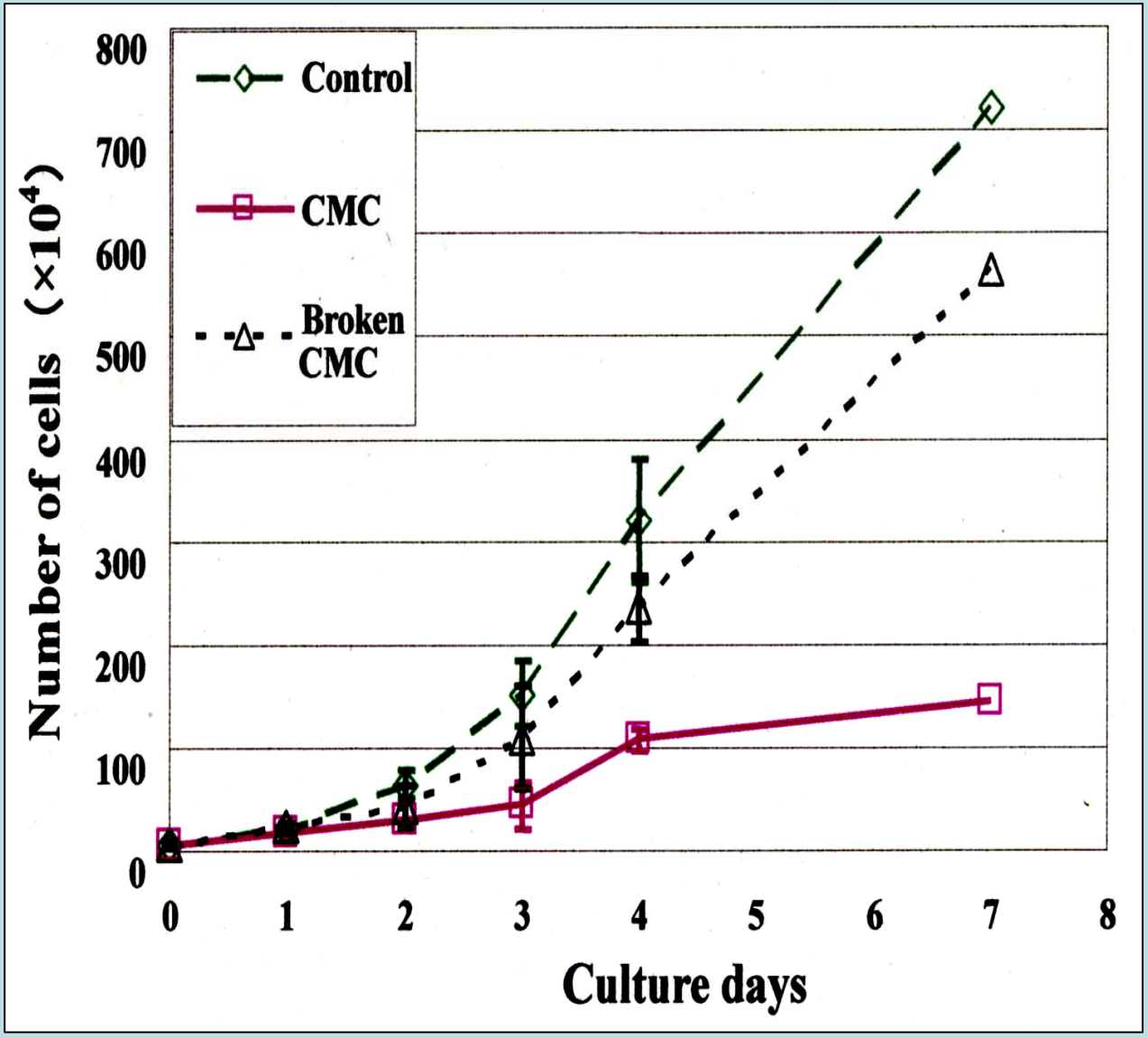
成分：〈モイストタイプ〉ポリアクリル酸アルキル、イソノナン酸イソトリデシル、メチルフェニルポリシロキサン、ミネラルオイル、トリ（カプリル・カプリン酸）グリセリン、パラフィン、硫酸Ｂａ、ポリエチレン、メトキシケイヒ酸オクチル、ポリアクリル酸メチル、セスキオレイン酸ソルビタン、霊芝エキス（黒霊芝、赤霊芝）、加水分解コラーゲン、炭素（カーボンマイクロコイル）、ビタミンAパルミテート、ビタミンE、ビタミンCリン酸マグネシウム、メチコン、BG、精製水、オレス－３リン酸、香料、マイカ、酸化チタン、酸化鉄

成分：〈パウダータイプ〉セリサイト、（タルク／ケイフッ化K）焼成物、窒化ホウ素、合成金雲母、ポリアクリル酸メチル、タルク、ジメチコン、メトキシケイヒ酸オクチル、マイカ、シリカ、コハク酸ジオクチル、（ジメチコン／ビニルジメチコン／メチコン）クロスポリマー、霊芝エキス（黒霊芝、赤霊芝）、加水分解コラーゲン、炭素（カーボンマイクロコイル）、パーフルオロカプリリルトリエトキシシリルエチルメチコン、ビタミンAパルミテート、ビタミンE、ビタミンCリン酸マグネシウム、ポリクオタニウム－６１、メチコン、BG、精製水、ステアリン酸亜鉛、パラベン、香料、酸化チタン、酸化鉄

NIPPON MENARD COSMETIC CO., LTD.
MADE IN JAPAN

Effect of CMCs for anti-breeding of Hela cell (human-uterus-neck-cancer-cell）（CMC : 0.04 wt%）

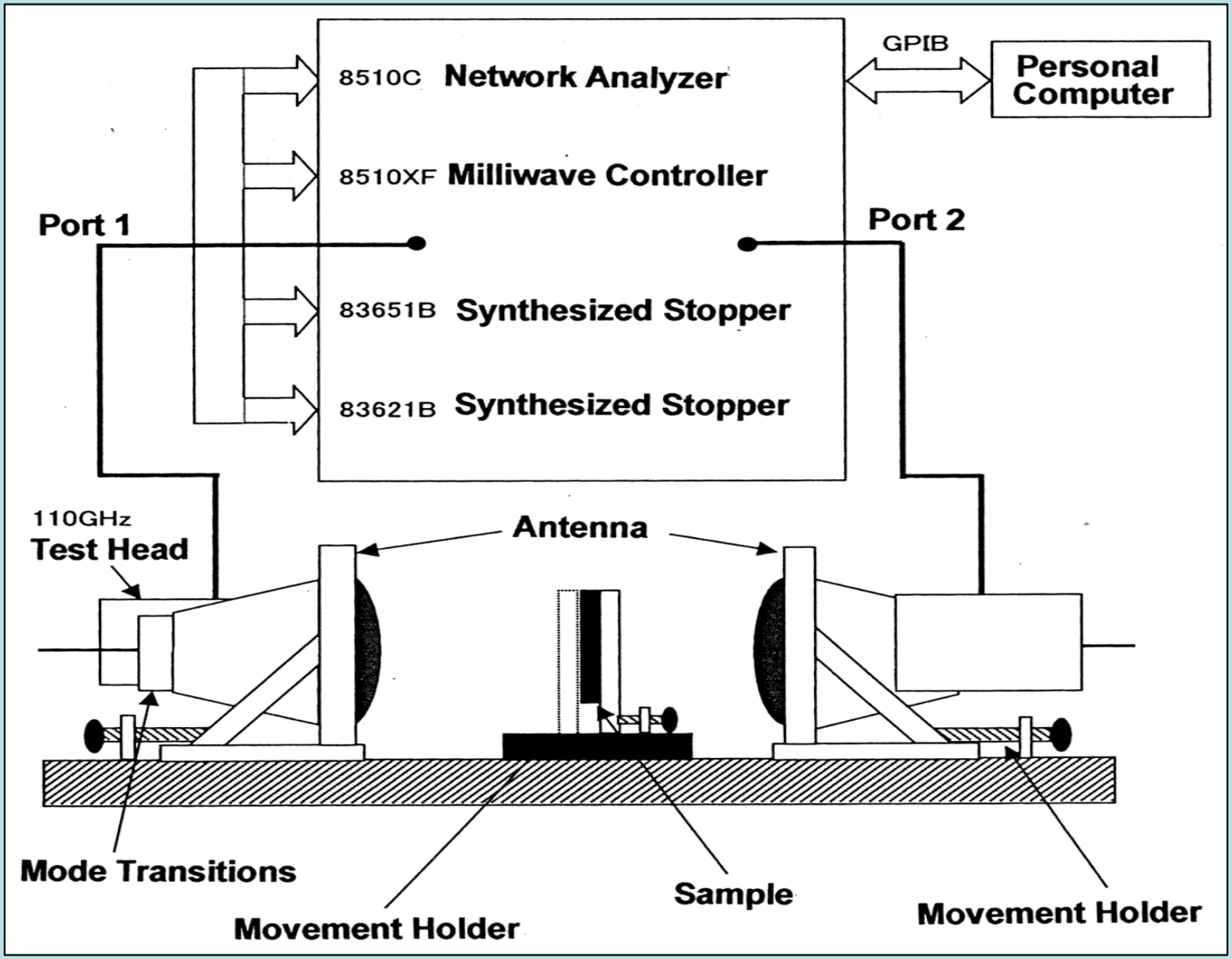
Applicable as cancer remedy medicine



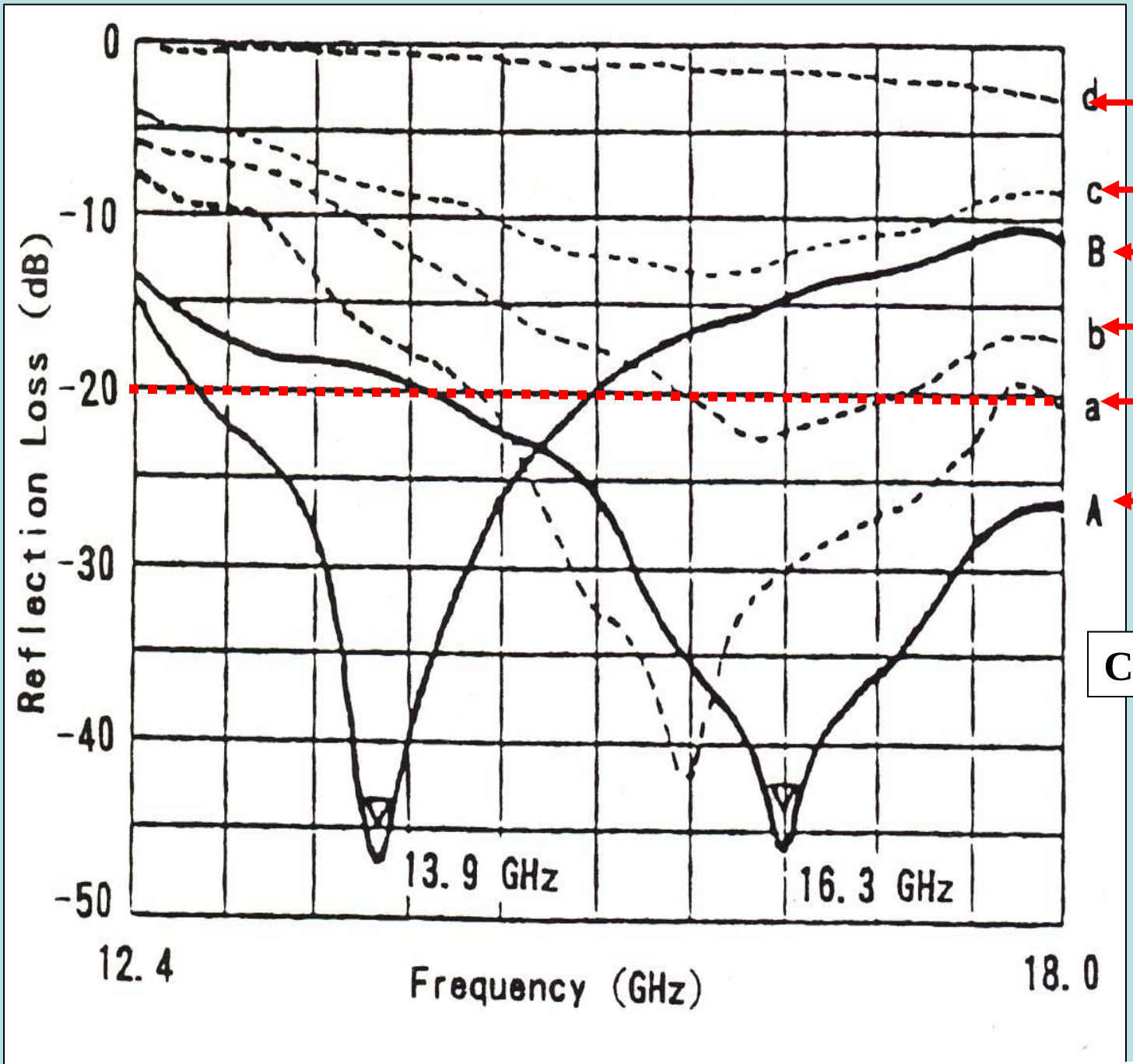
This figure shows the effect of CMC on the breeding of cancer cell. When the CMC was added by 0.04 wt%, the number of cancer cell after 7 day breeding is about 20% against control sample.
That is, the CMC can be applicable as a cancer remedy medicine.

Why CMC is affective for the recovery of skin cell or for cancer remedy is not known yet.

Application to electro microwave absorber



Free space microwave measurement system (JFCC-HVS)



Carbon powder(d)

Carbon powder(c)

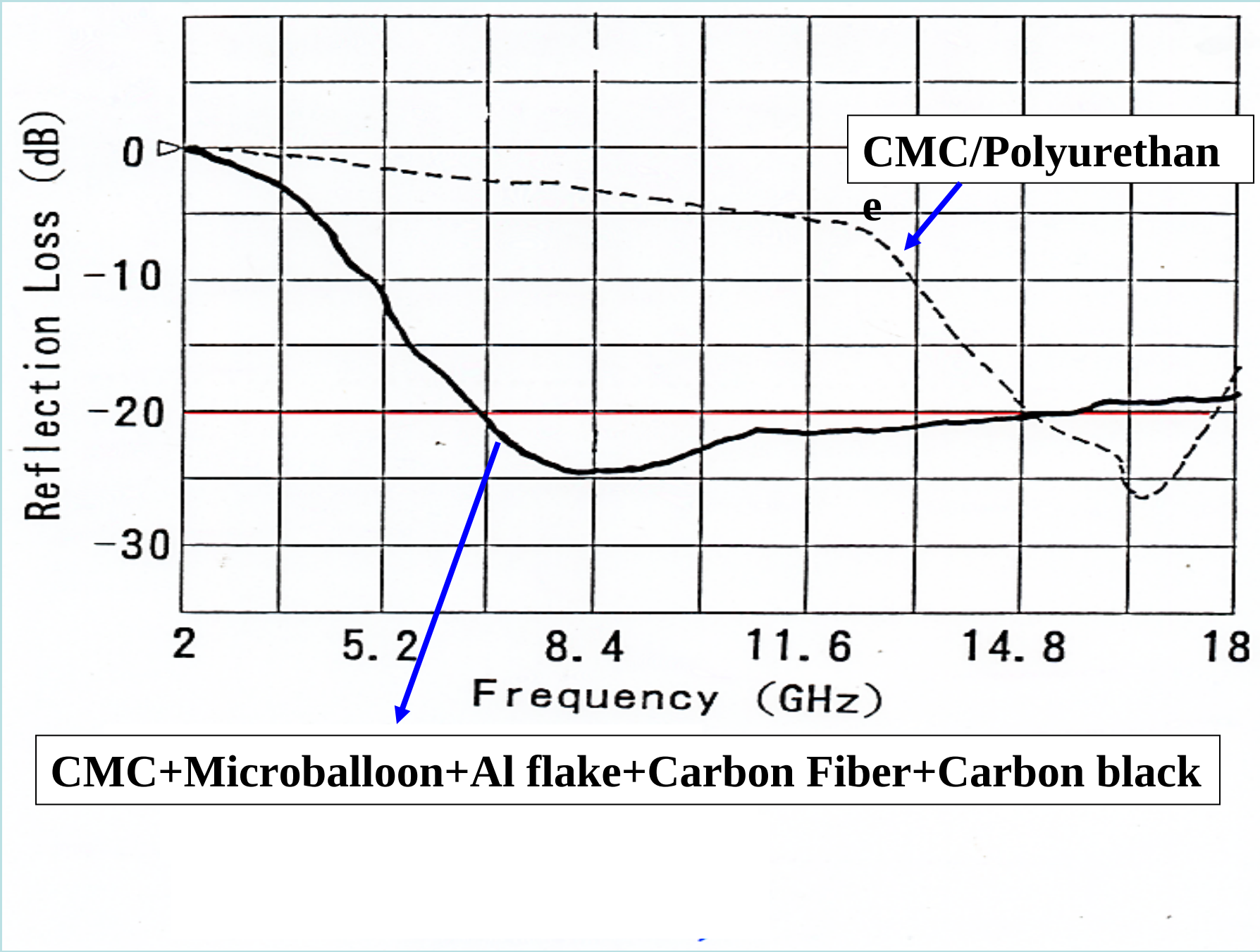
CMC(B)

Carbon powder(b)

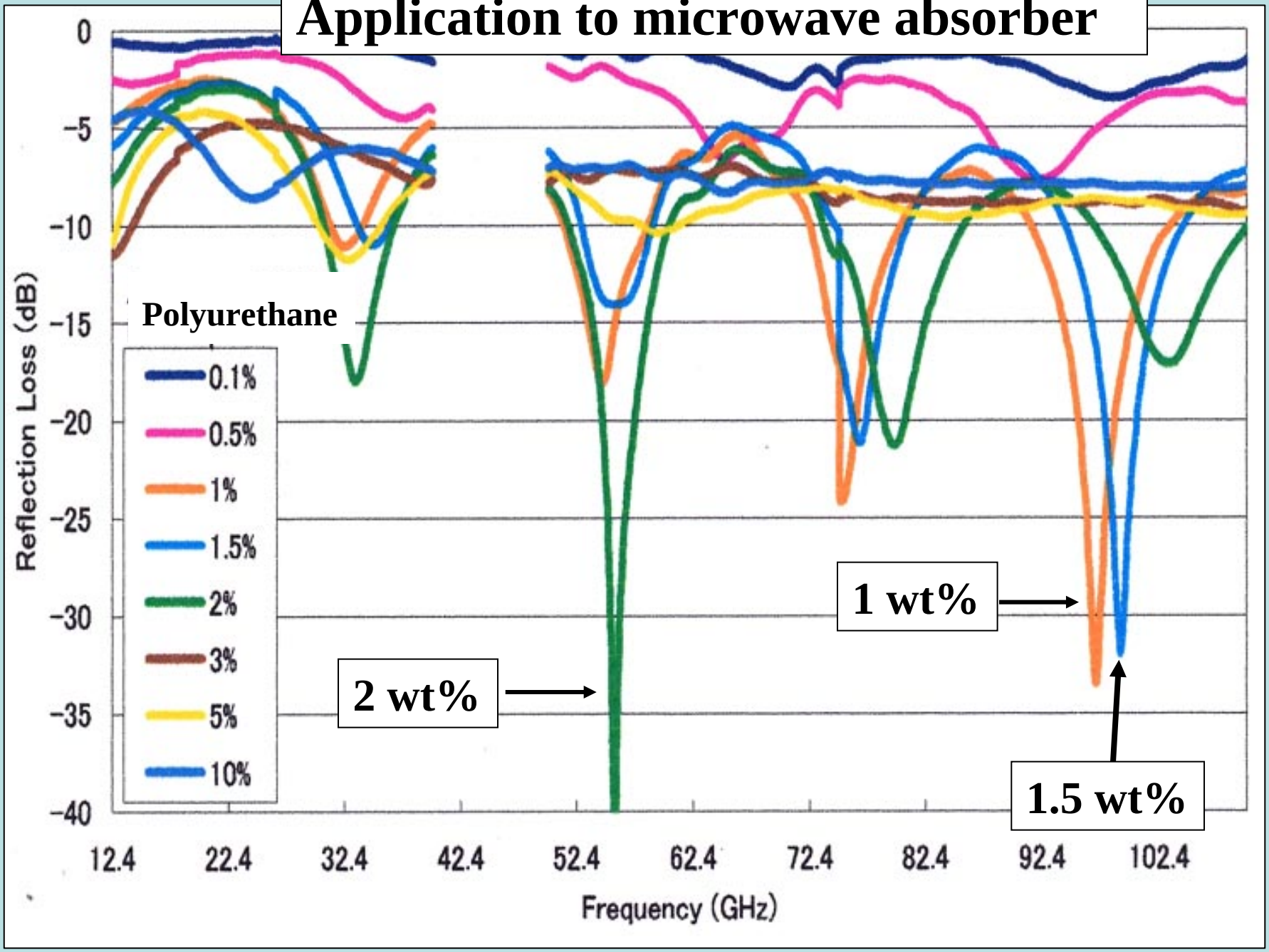
Carbon powder(a)

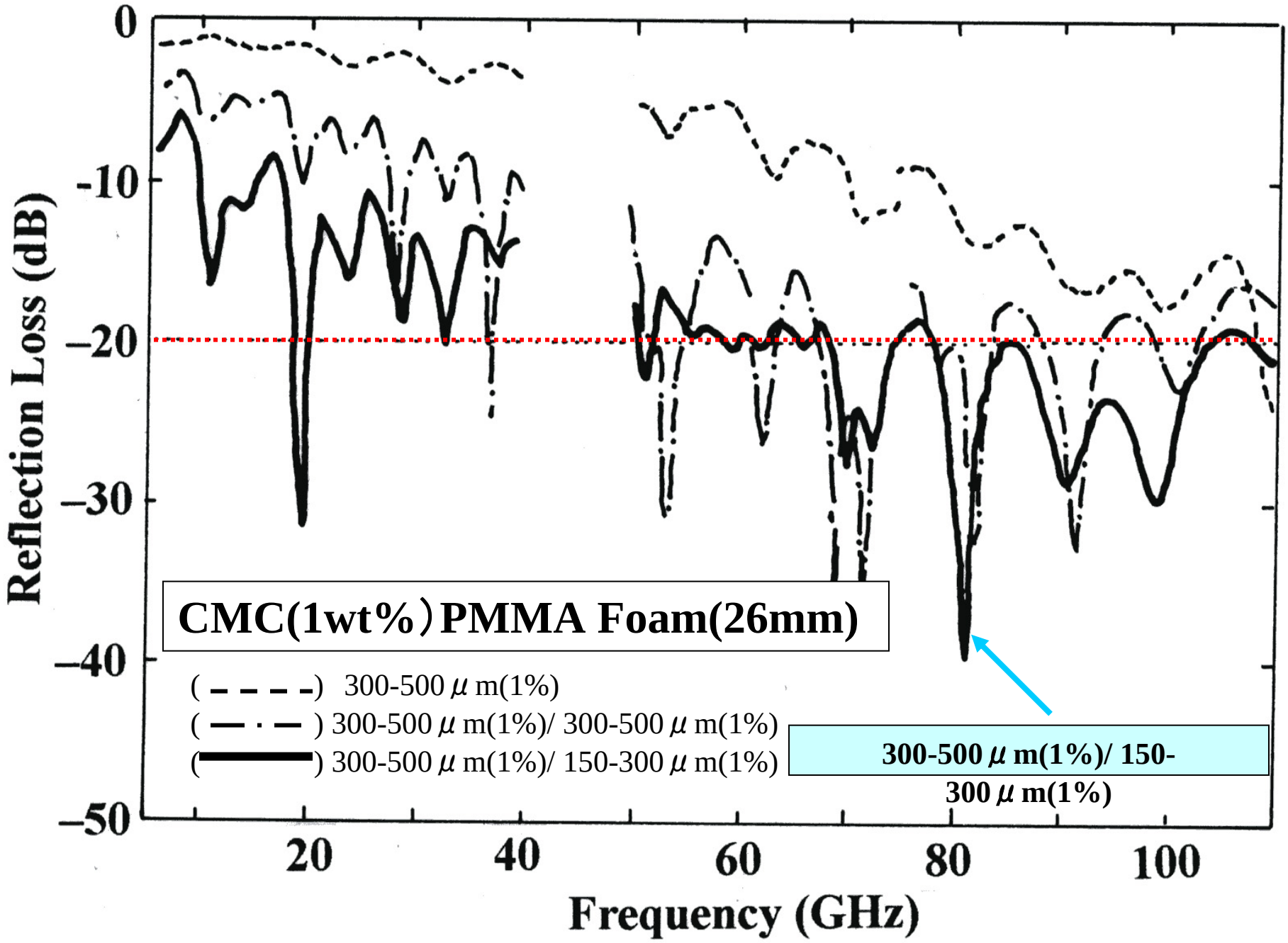
CMC(A)

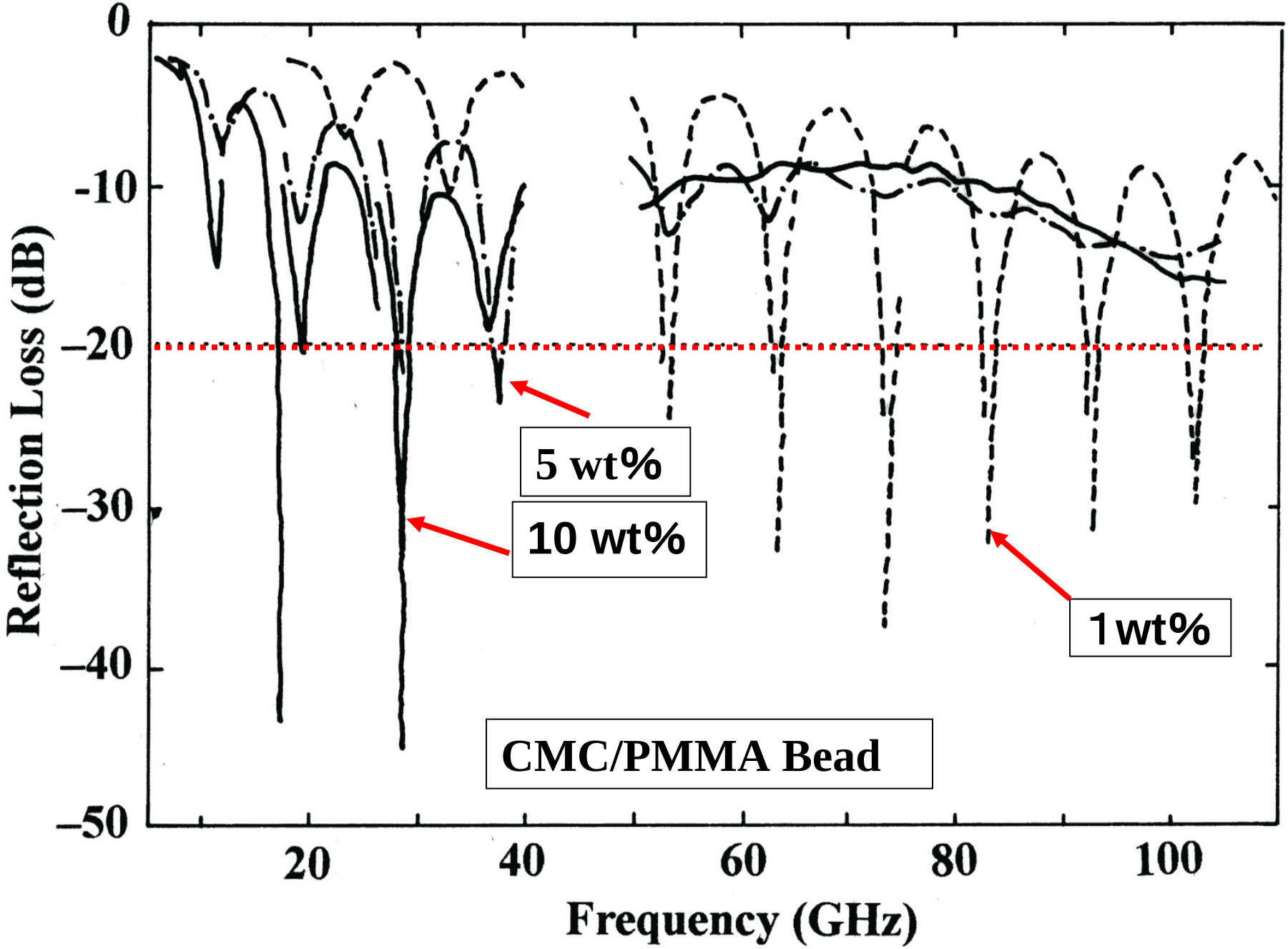
Coil length:<1mm

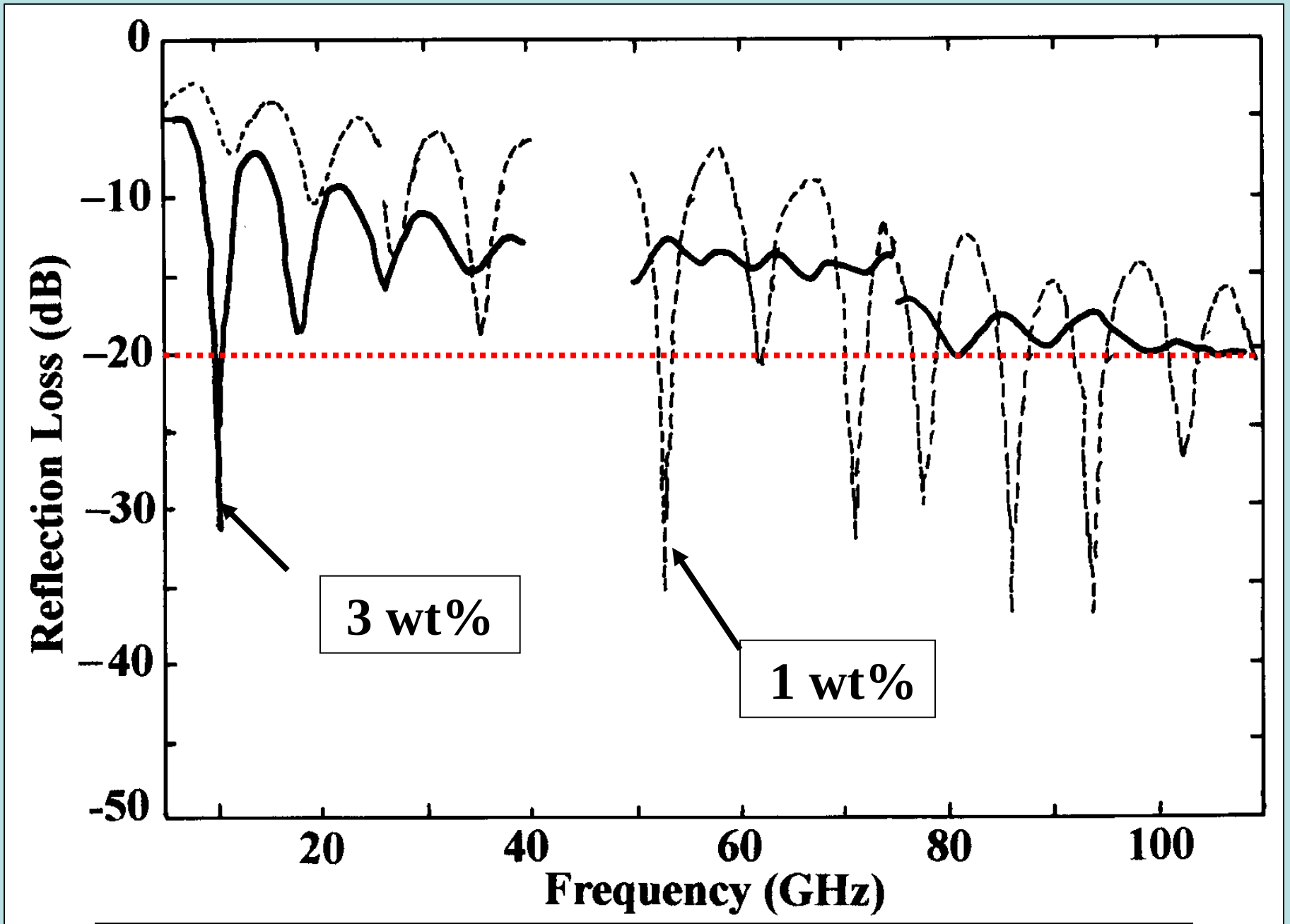

CMC/Polyurethane
Reflection Loss (dB)
0
-10
-20
-30
2
5.2
8.4
11.6
14.8
18
Frequency (GHz)
CMC+Microballoon+Al flake+Carbon Fiber+Carbon black

Application to microwave absorber

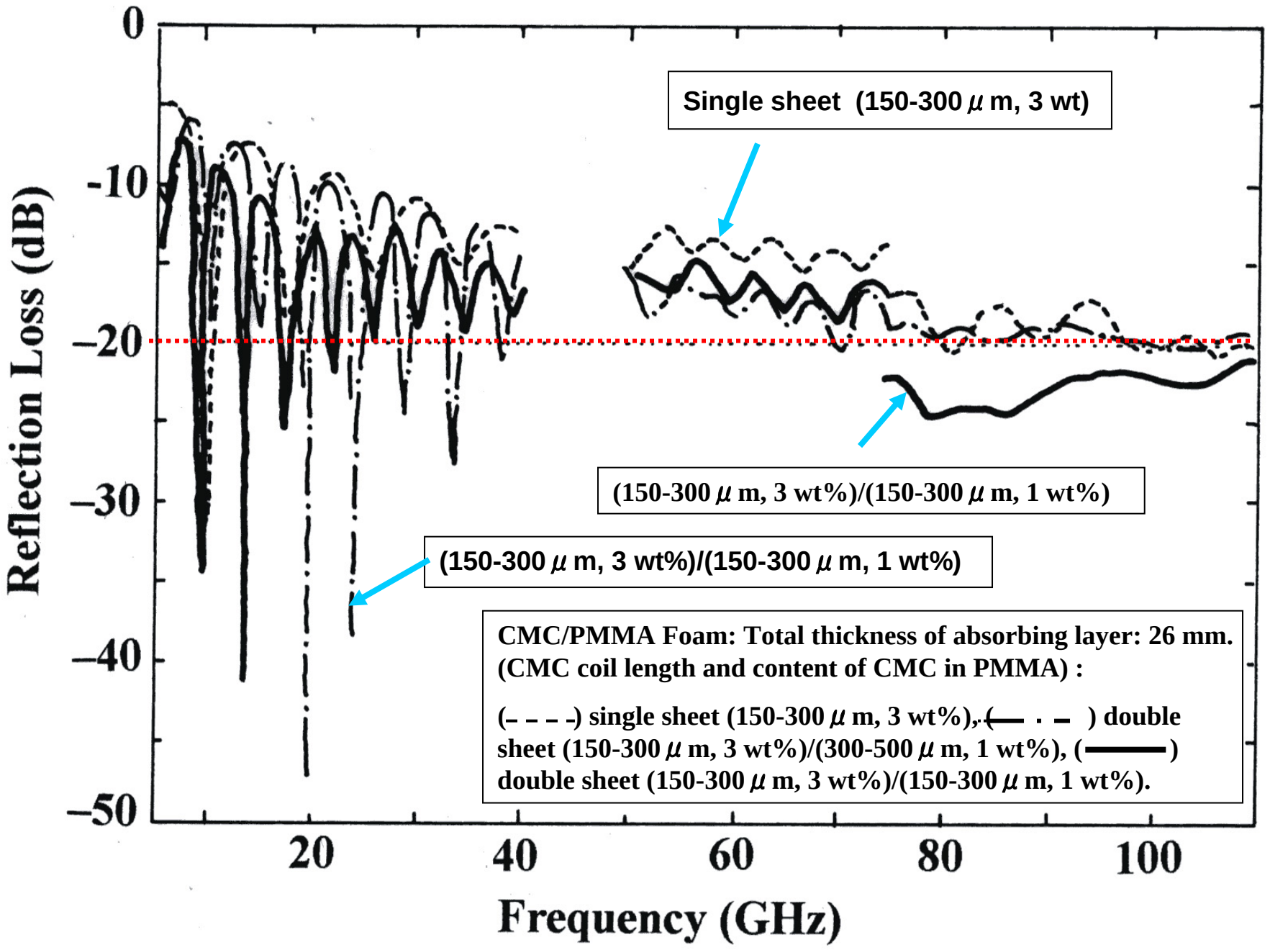



0
-10
–20
–30
–40
–50
Reflection Loss (dB)
20
40
60
80
100
Frequency (GHz)
CMC(1wt%）PMMA Foam(26mm)
(- - - -) 300-500 μ m(1%)
(— · —) 300-500 μ m(1%)/ 300-500 μ m(1%)
(———) 300-500 μ m(1%)/ 150-300 μ m(1%)
300-500 μ m(1%)/ 150-300 μ m(1%)

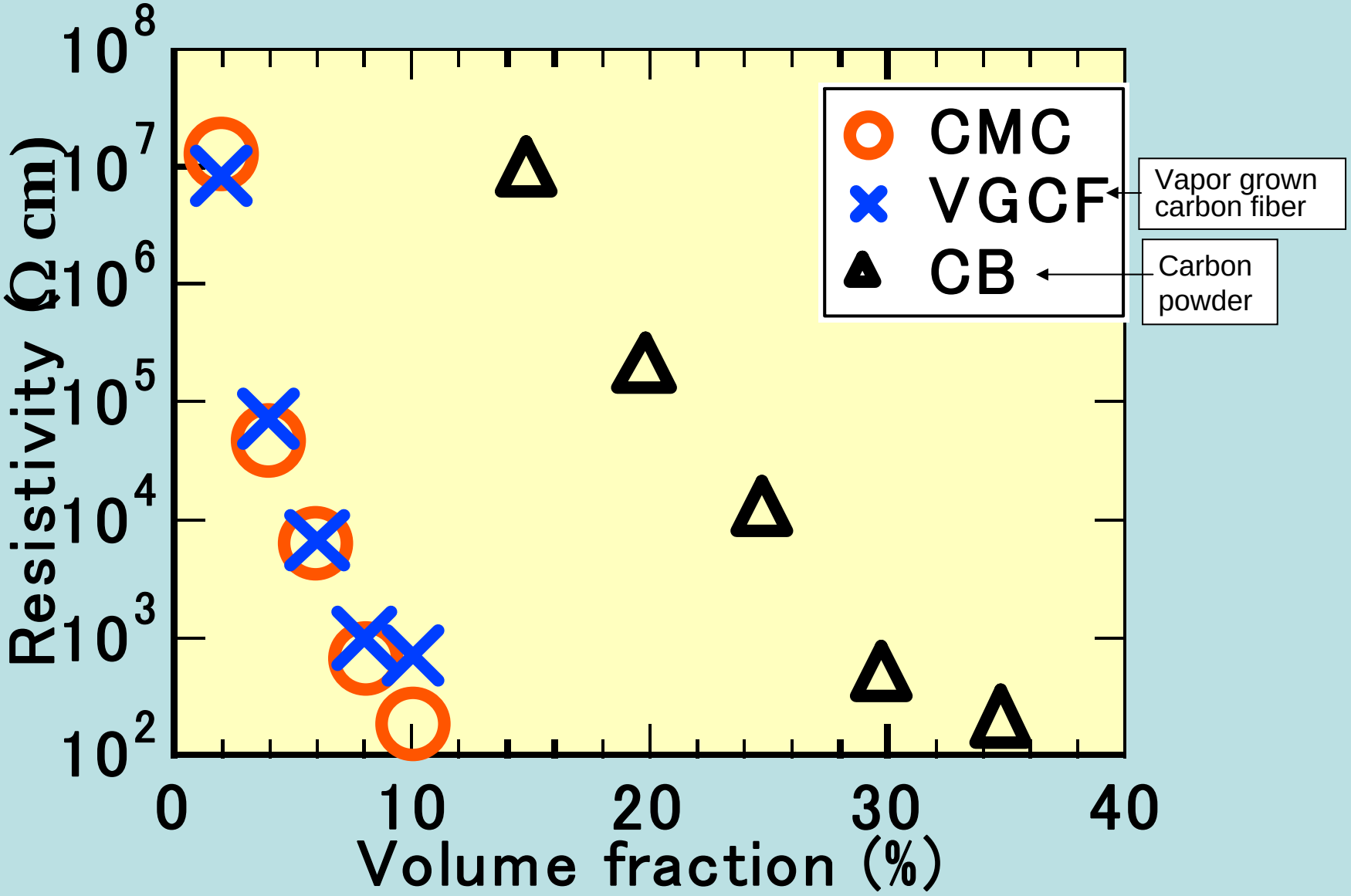

0
-10
–20
–30
–40
–50
Reflection Loss (dB)
20
40
60
80
100
Frequency (GHz)
5 wt%
10 wt%
1wt%
CMC/PMMA Bead



Reflection loss of CMC/PMMA foams (CMC:150－300 μm)

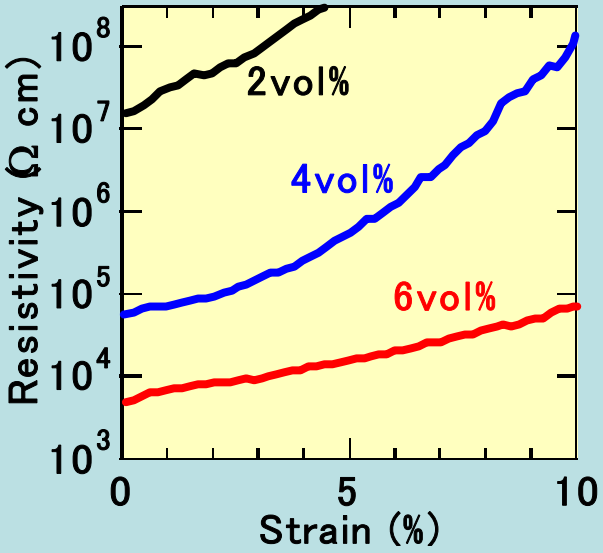

0
-10
–20
–30
–40
–50
Reflection Loss (dB)
20
40
60
80
100
Frequency (GHz)
Single sheet (150-300 μ m, 3 wt)
(150-300 μ m, 3 wt%)/(150-300 μ m, 1 wt%)
(150-300 μ m, 3 wt%)/(150-300 μ m, 1 wt%)
CMC/PMMA Foam: Total thickness of absorbing layer: 26 mm.
(CMC coil length and content of CMC in PMMA) :
(– – – –) single sheet (150-300 μ m, 3 wt%), (— · –) double sheet (150-300 μ m, 3 wt%)/(300-500 μ m, 1 wt%), (————) double sheet (150-300 μ m, 3 wt%)/(150-300 μ m, 1 wt%).

Change in electrical resistivity of CMC/polysilicone composite sheet in relation with the addition amount of CMC



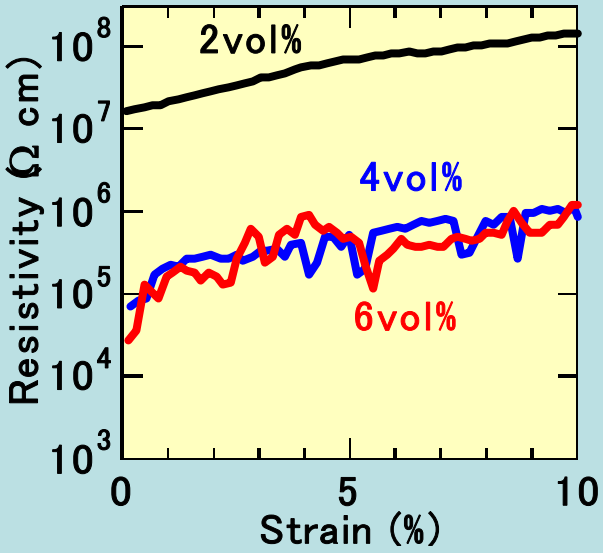
Change in electrical resistivity of composites under applying compression stress of 0.1~0.2MPa)

CMC composite



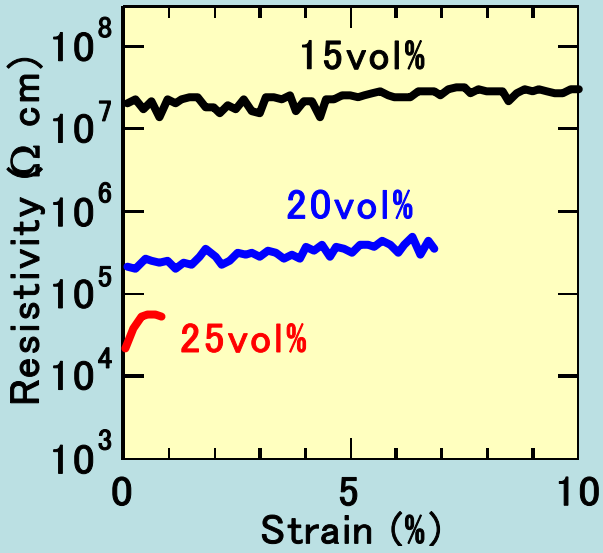
(Vapor Grown Carbon Fiber)

VGCF composite



(Carbon Black)

CB composite



for CMC(4vol%) composite

Applicable as a tactile sensor element

Under applying load of 0.1～0.2 MPa (1～2 kgf/cm^2)

→

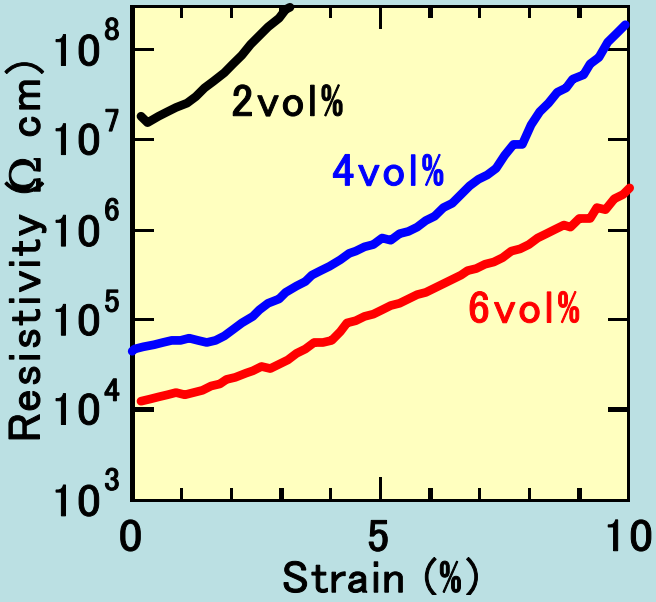
Under the deformation of 10% compression or tensile stresses

→

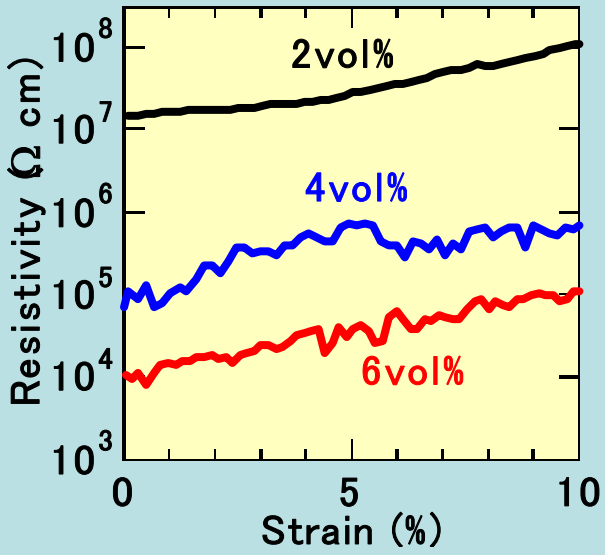
Changing in electrical resistivity by 1,000 times

Change in electrical resistivity of composites under applying compression stress

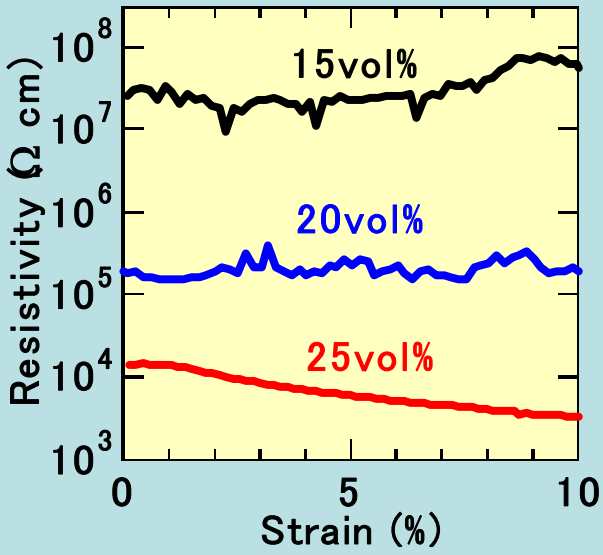
CMC Composite



VGCF composite



CB composite



Model of various receptors of human skin
(by Prof. T. Maeno of Keio Univ.)

Finger Prints

1) **Meissner's corpuscle is a helical receptor of cocoon-like forms, which is formed by the coiling of the terminal of nerves fibers.**
2) **Meissnor's corpuscles are present in two arrays under finger prints with the density of 1500/cm^3.**

3) **Meissnor's corpuscles shows a high sensitivity and discrimination ability to applied physical stimuli.**

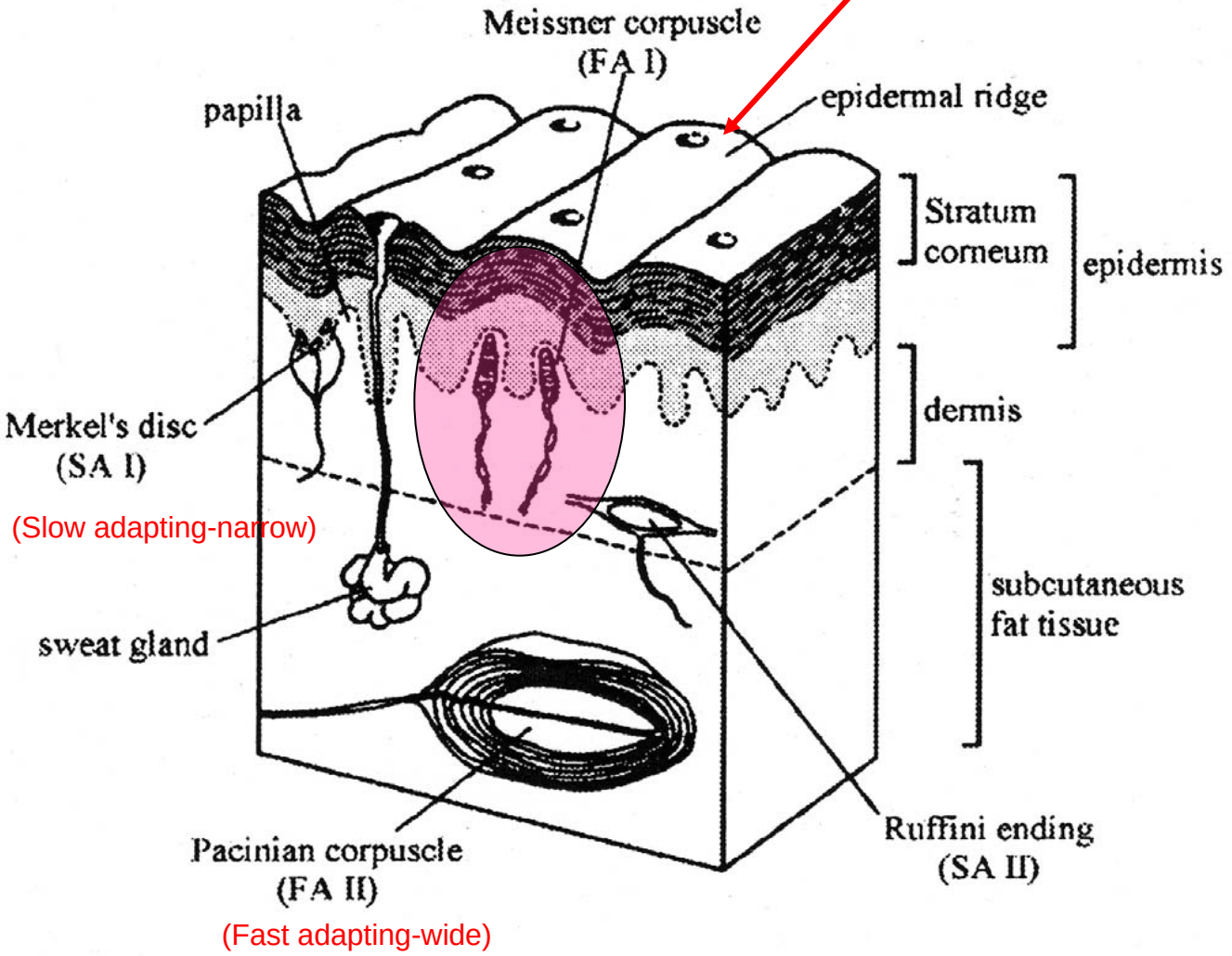


図 1　指腹部組織と触覚受容器 [2)]

- **Human skin has very high sensitivity and discrimination ability to various stresses and stimuli, such as, mechanical loading, pressing, picking, sticking, rubbing, temperature, sound, etc.**

- **So, It is expected that if CMC is embedded into elastic rubbers, high tactile sensing and discrimination ability corresponding to that of human skin may be obtained.**

- **According to this concept, we have prepared artificial skin with tactile sensing properties. These sensor elements were made of CMC and elastic polysilicone rubber composite sheet.**

- **So, it is expected that if CMC is embedded into elastic rubbers, high tactile sensing and discrimination ability comparable to that of human skin may be obtained.**

- **According to this concept, we have prepared artificial skin with tactile sensing properties. These sensor elements were made of CMC and elastic polysilicone rubber composite sheet.**

Meissner's Corpuscles

- 3D helical-coiled nerve fibers (Proteins)
- Single-helix ?
- Diameter of helix : 40-70 μm
- Length of helix : 20-150 μm

Carbon Microcoils (CMC)

- 3D helical-coiled carbon fibers (Pure carbon)
- Double-helic or single-helix
- Diameter of coils : 1-20 μm
- Coil Length : 50-500 μm

Relationship between Meissner's corpuscle and carbon micorcoils

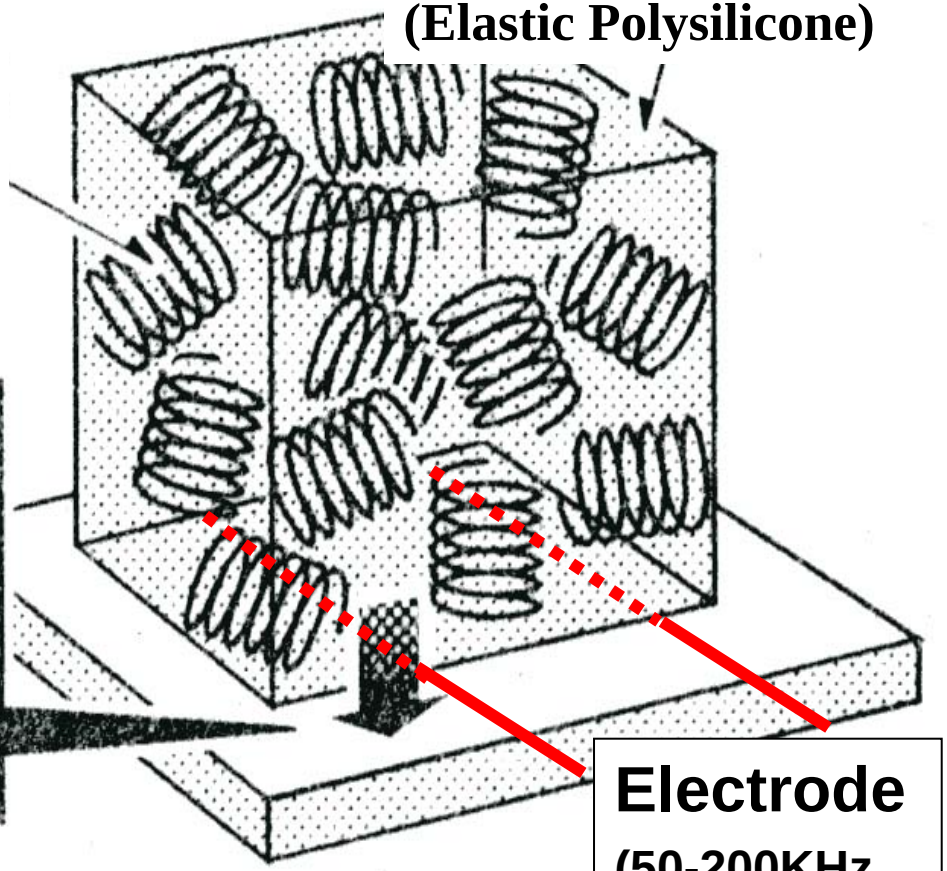
There are many similarity between Meissner's corpuscle and carbon microcoils in the point of conformation and size

Model of CMC/Polysilicone Micro-sensor Element

Structure of CMC Sensor element

Carbon microcoils
(90-500 μ m, 1~5wt%)

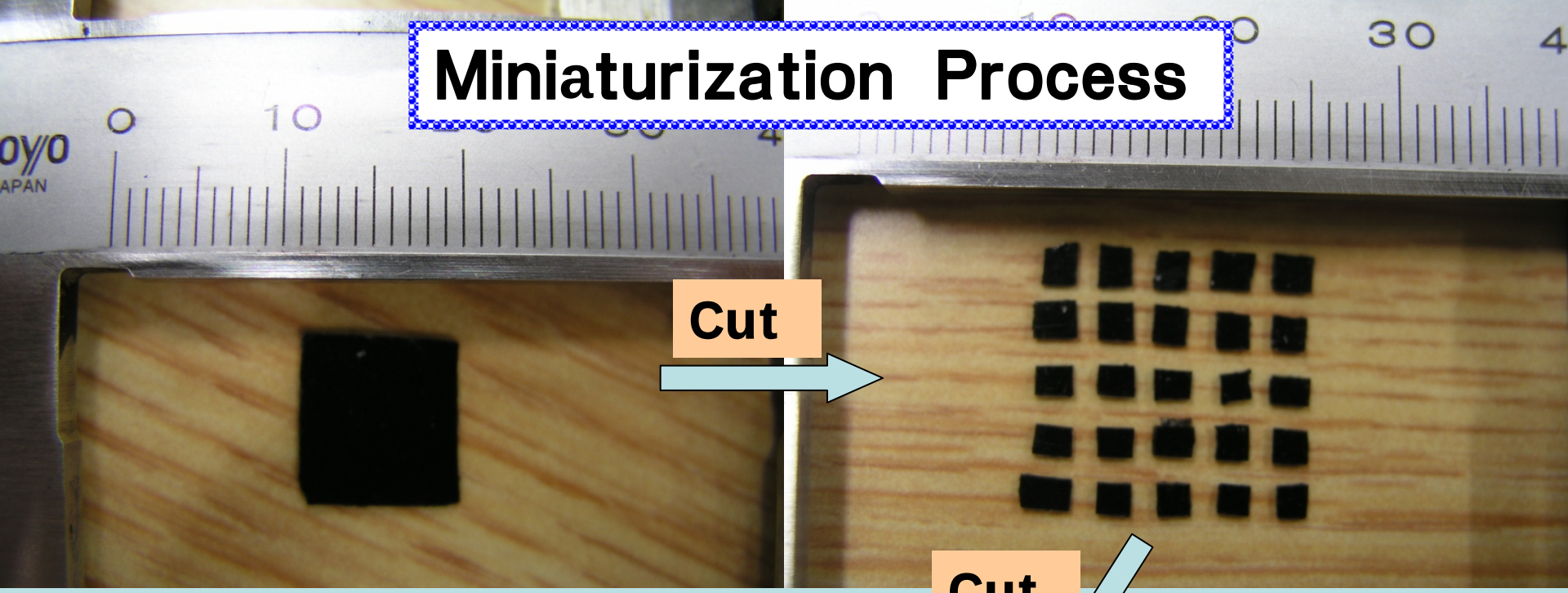
Matrix
(Elastic Polysilicone)

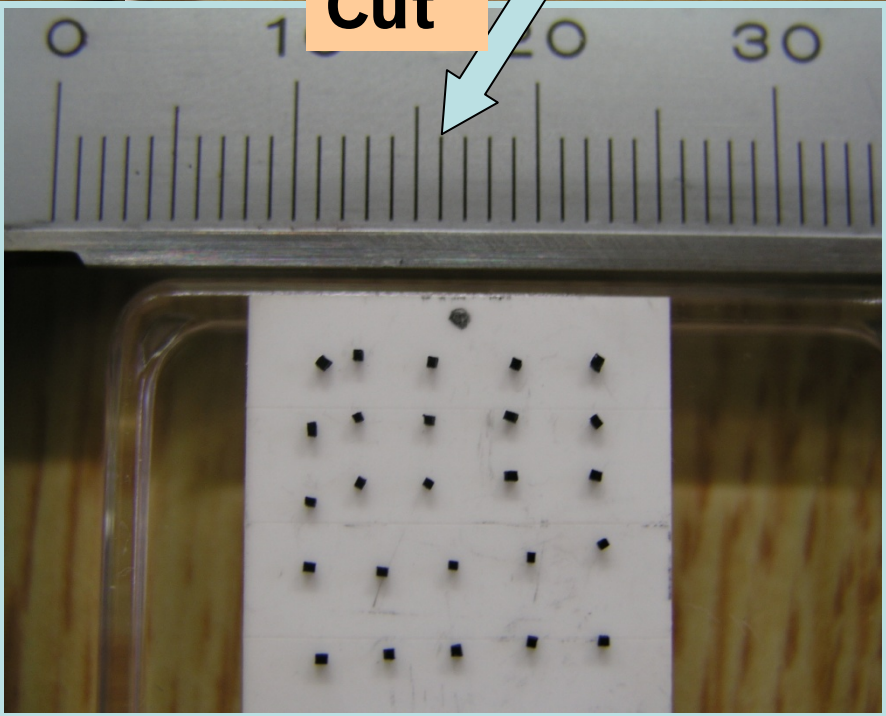


Electrode
(50-200KHz, 0.5-10V)

Sensing applied very small load, pressure, temperature, electromagnetic waves, sound, etc. with very high sensitivity and discrimination ability.

Miniaturization Process

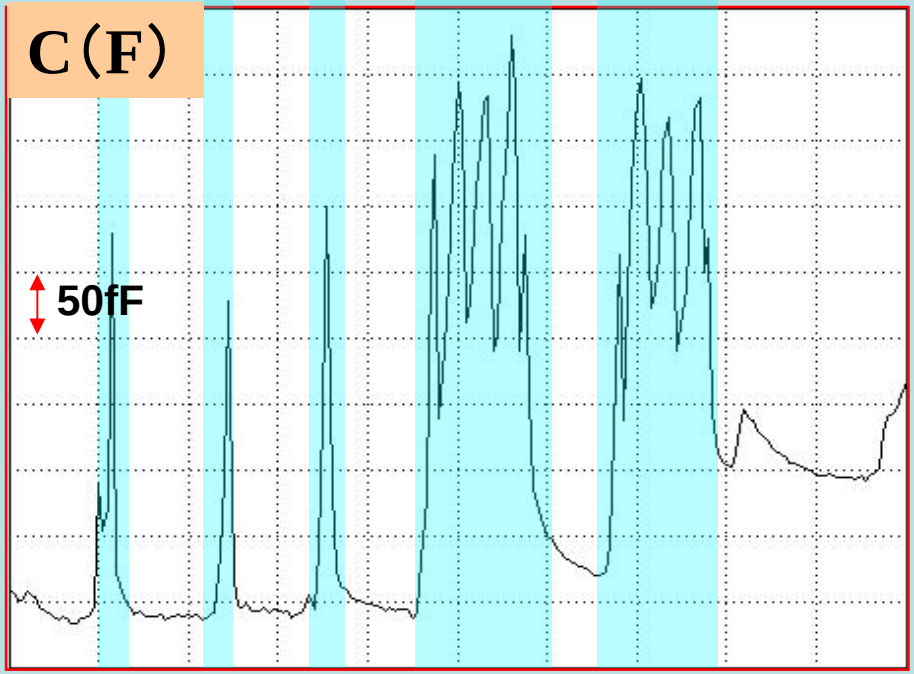


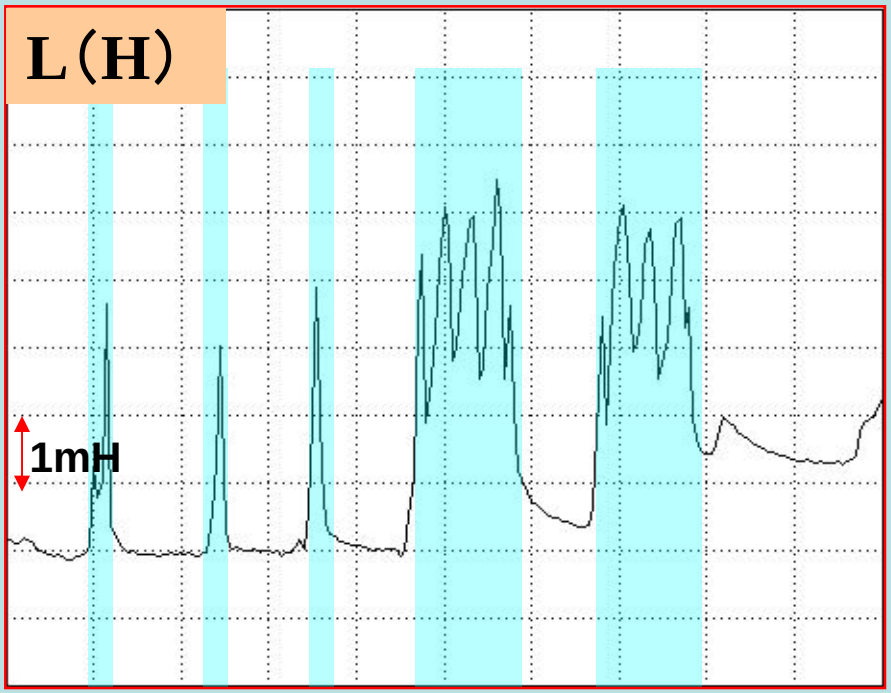


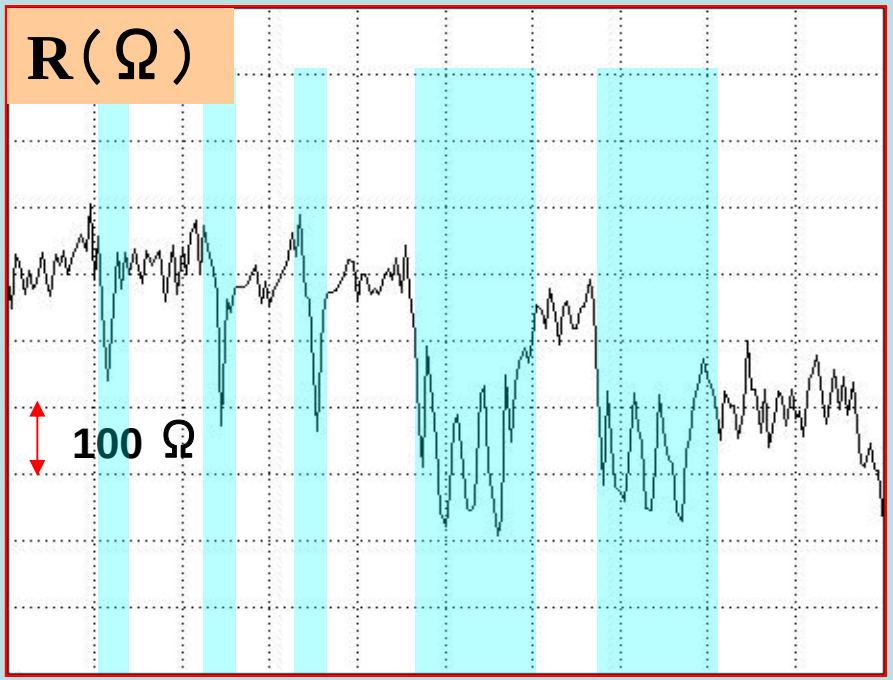
The CMC sensor element have a very simple structure, composite of CMC and elastic matrix, and can be easily miniaturizing by cutting successively the large sheets to small sheets or blocks by using conventional cutter or ultrasonic cutter. The minimum size of obtained sensor element was about 100x80x80mm^3

Change in LCR parameters of micro-sensor （100x100x100 μm^3)

Matrix： Elastic silicone resin
Coil Length： 500-500 μ m
Coil Diameter： 1-10 μ m
Addition amount： 5wt%
Load： 0.5gf



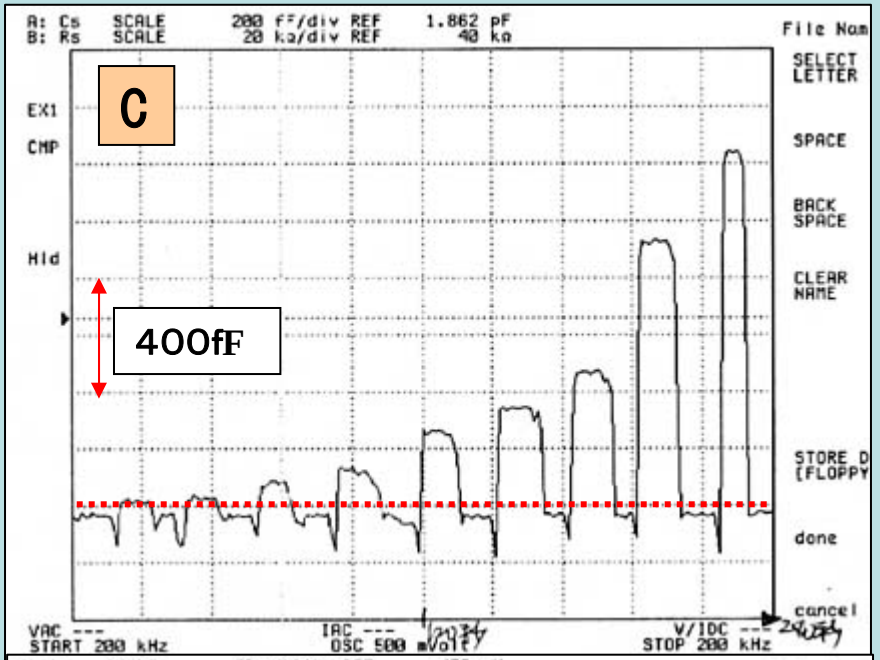


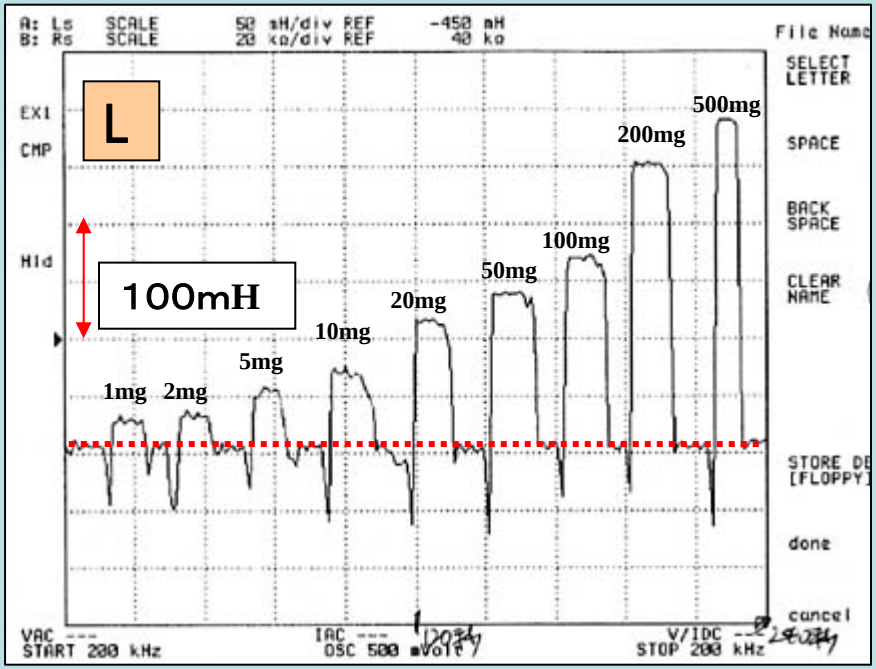


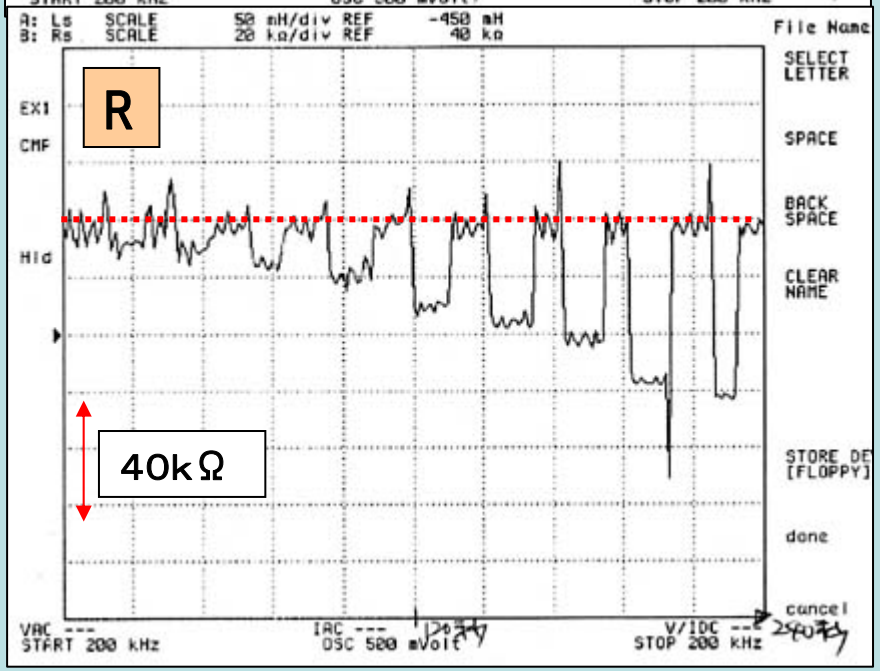
Change of LCR parameters under applying very small loads

Addition amount of CMC: 1wt%
Coil Length: <300 μm
Thickness of element：100 μm
Separation of electrode: 2.5mm

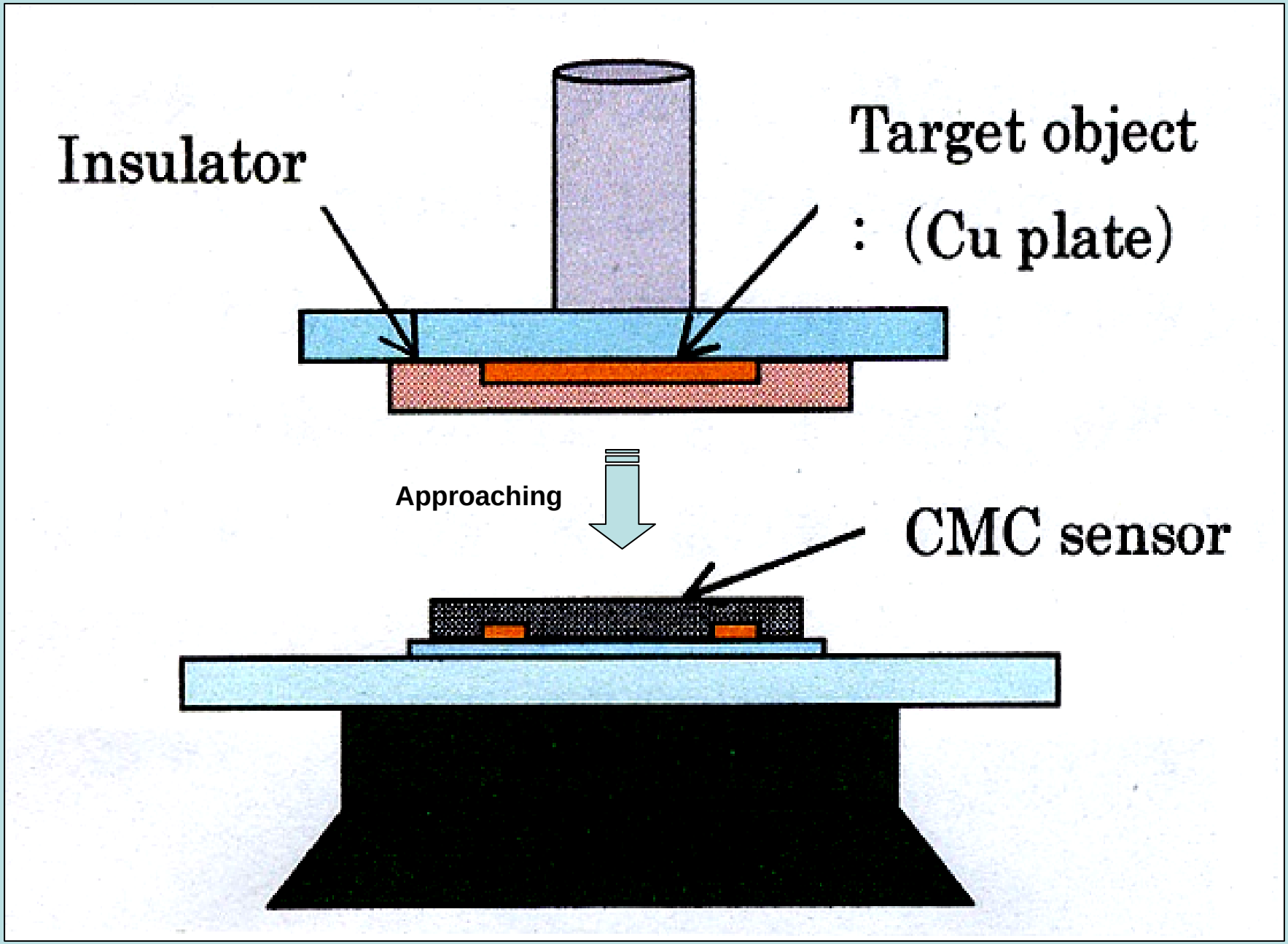
Minimum detectable load：1mgf (comparable to human skin)





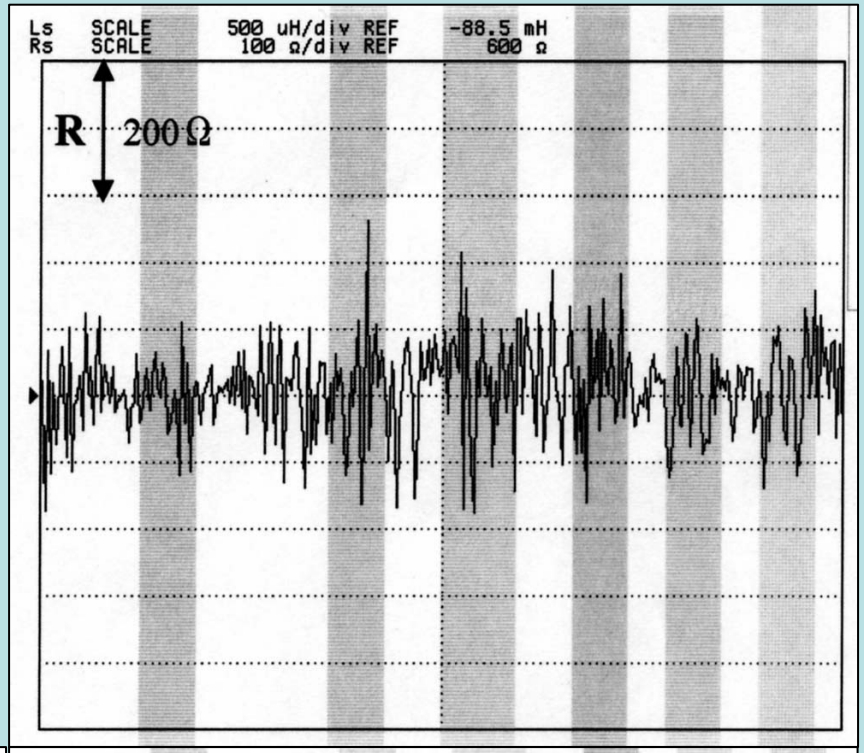


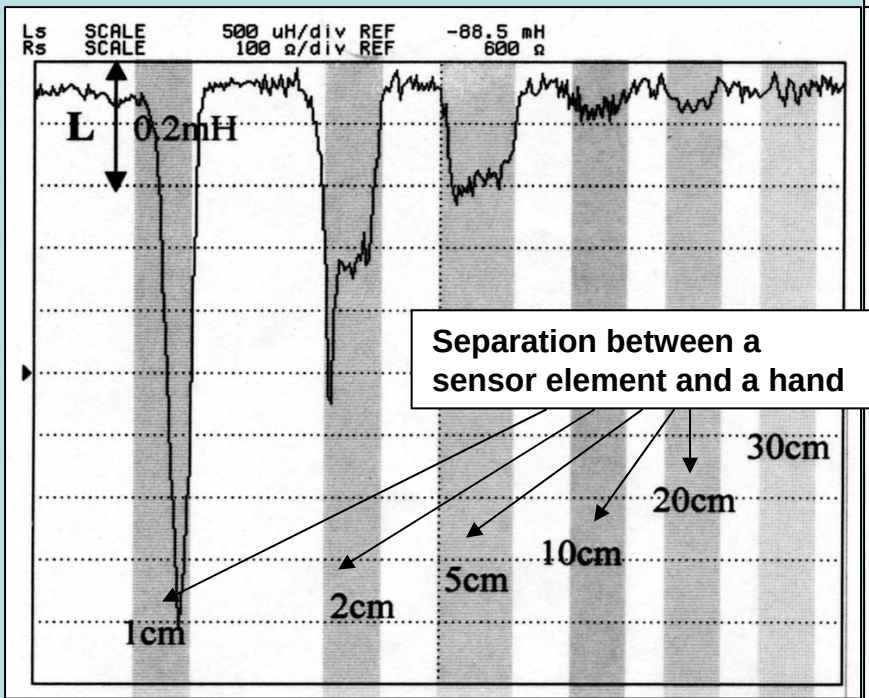
The CMC sensor element has proximity sensing property as well as tactile sensing property

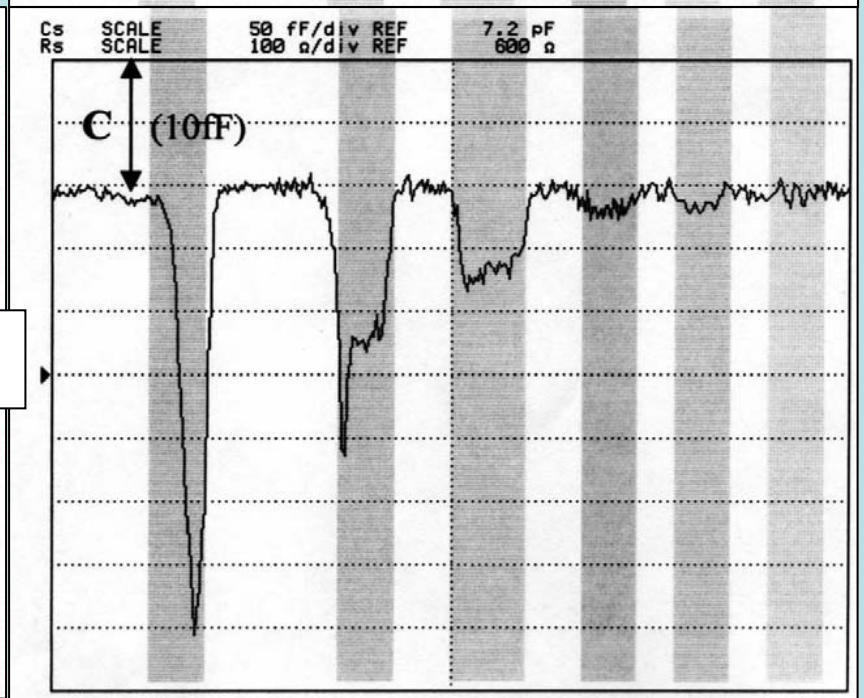


Change in LCR parameters under approaching a hand to CMC sensor element

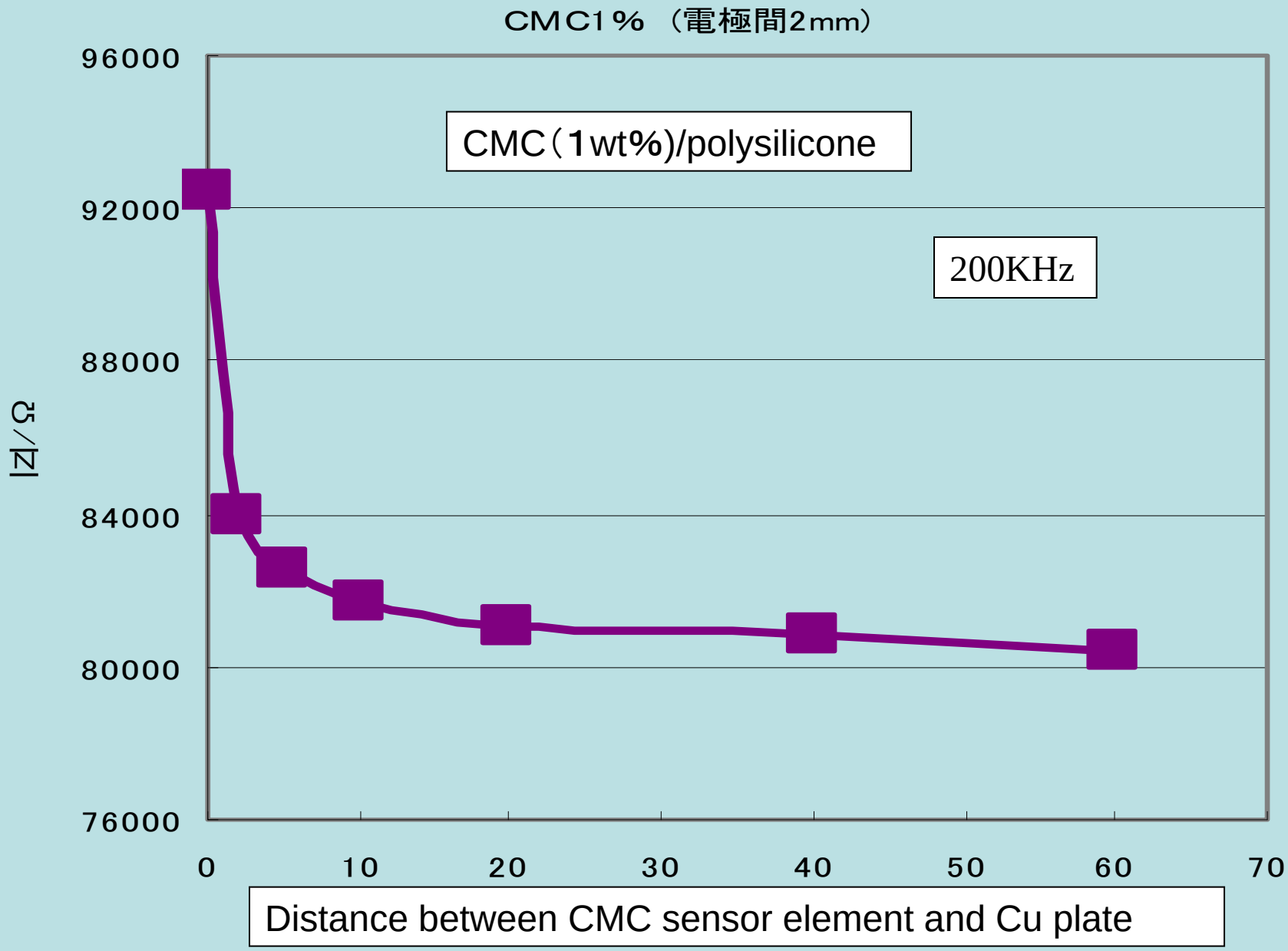
The CMC sensor element can detect accessing substances to the elements without touching.



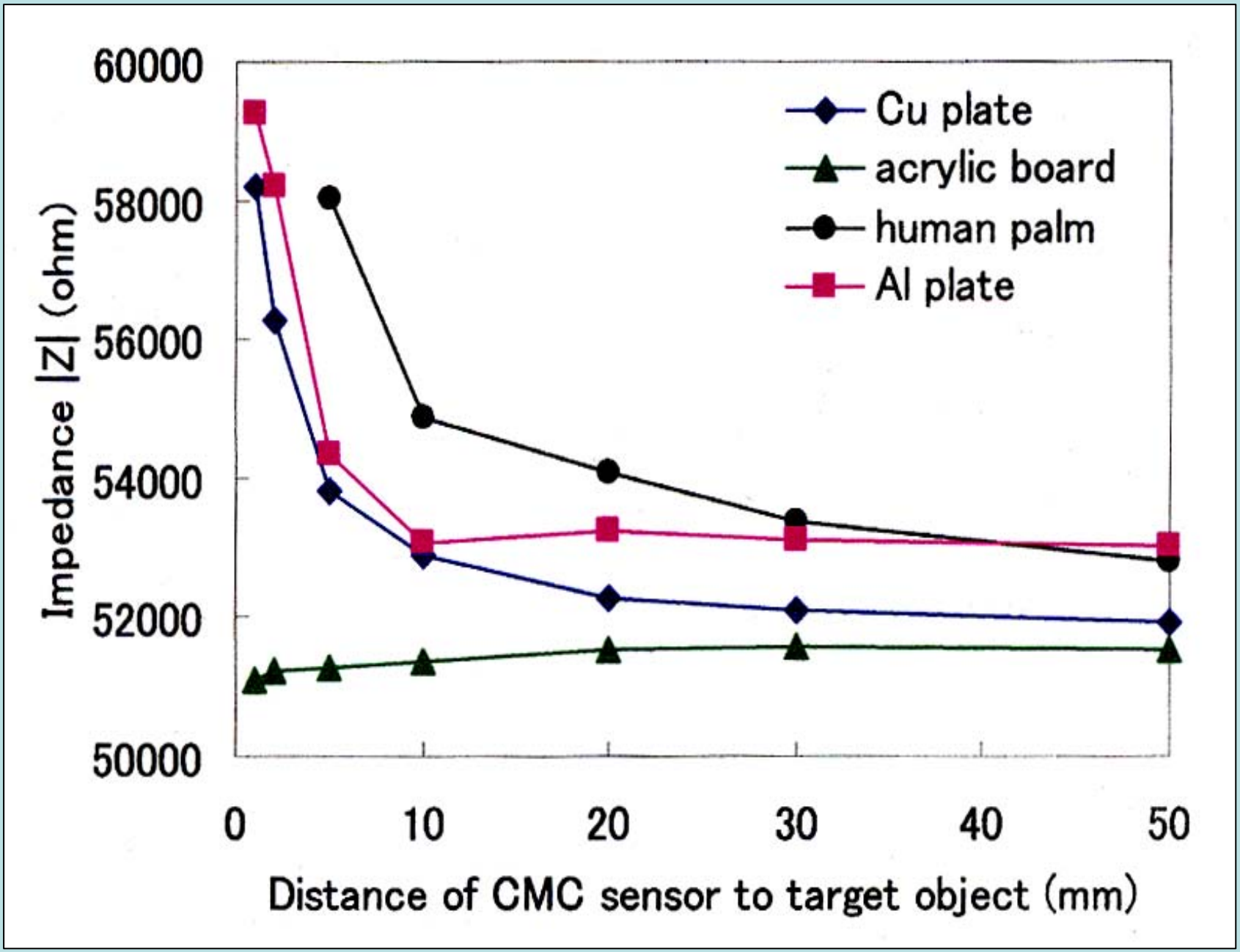




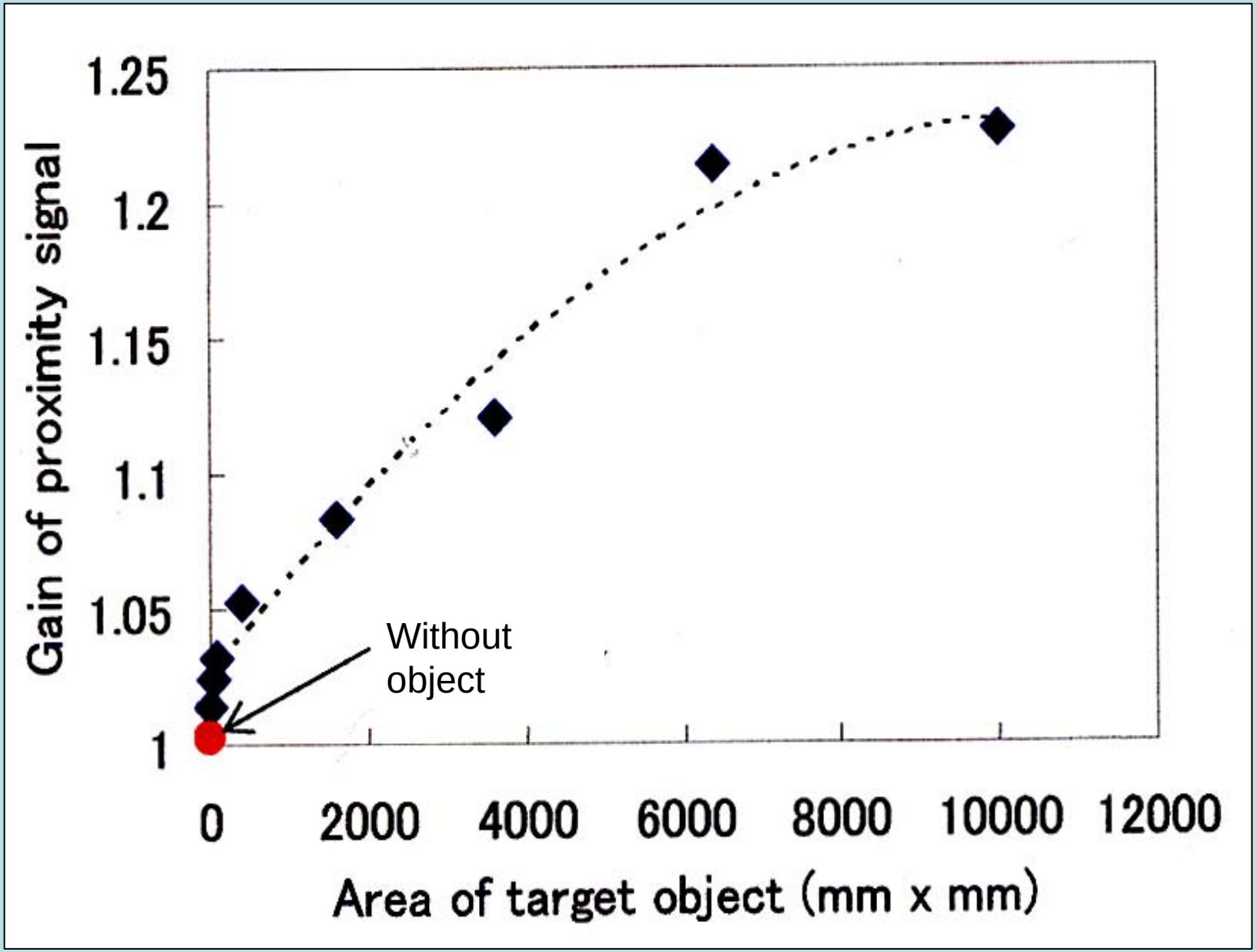
Change in impedance (z) of the CMC sensor element under approaching and touching to a Cu plate

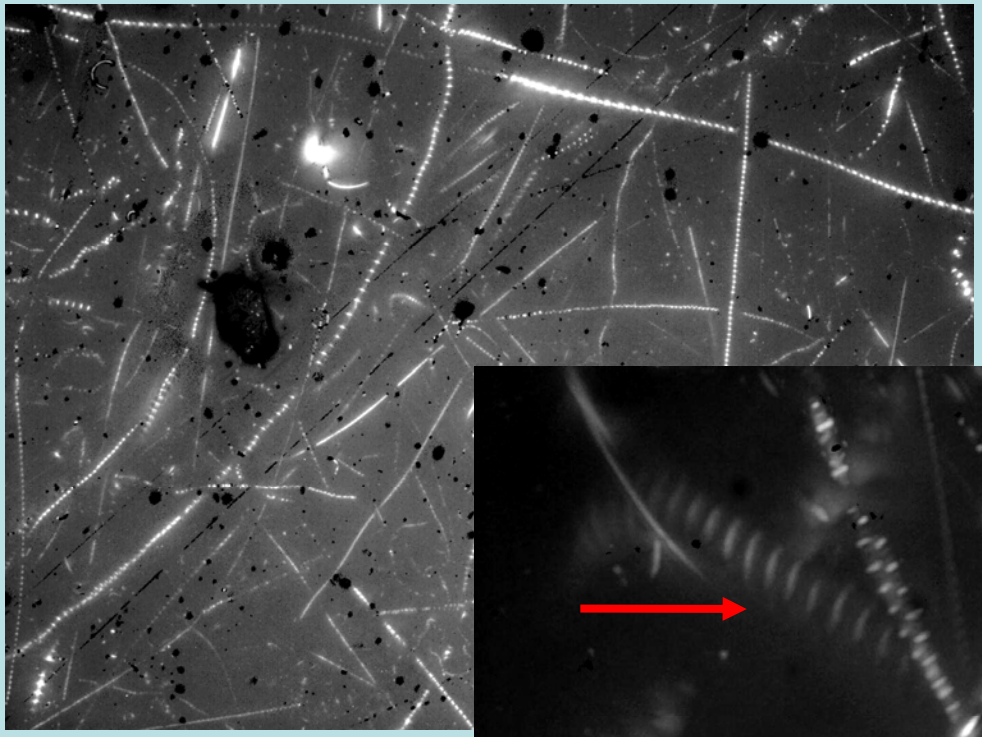


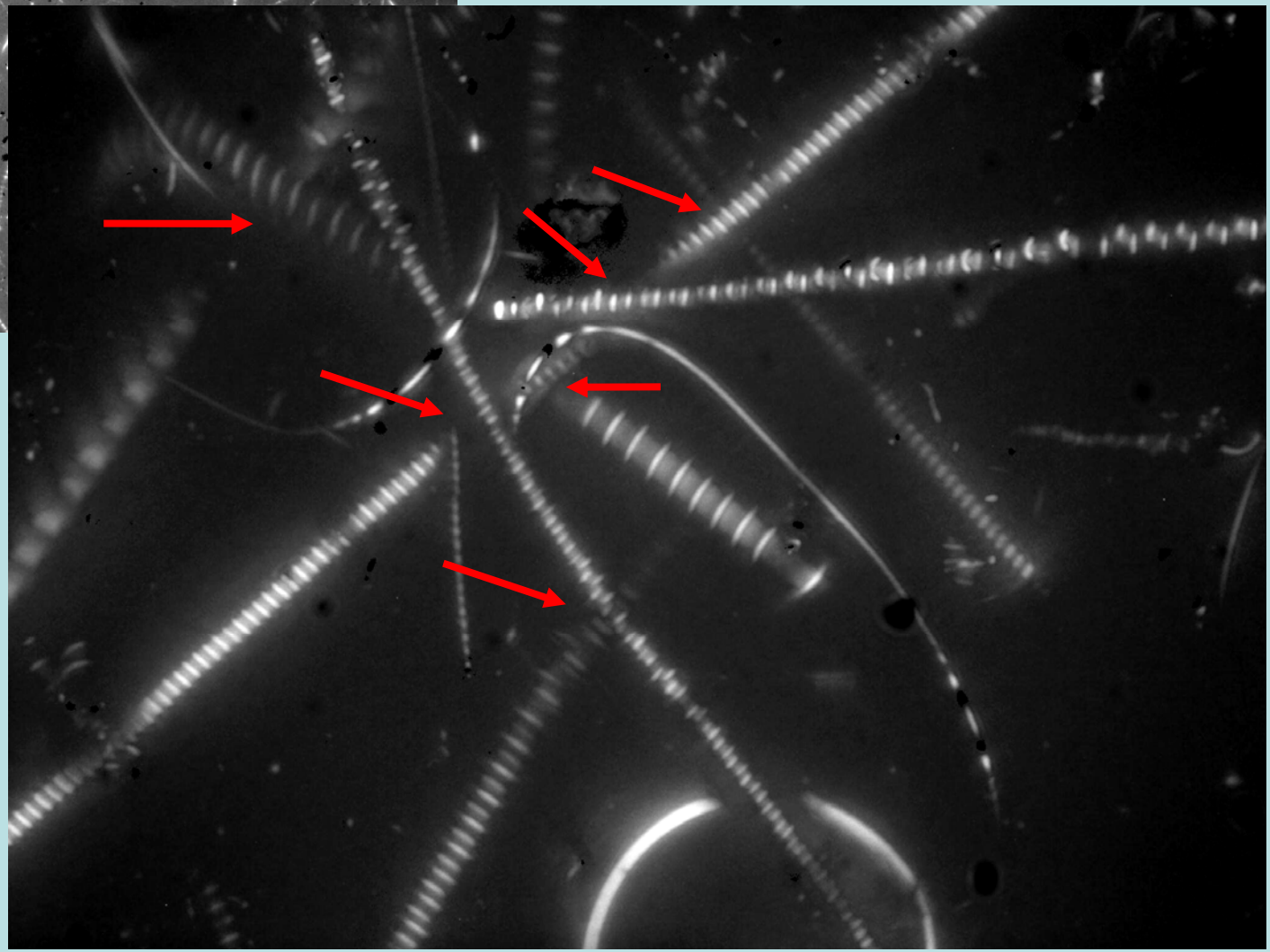
Effect of target substances on the change in impedance



Influence of the area of target object on the gain of proximity signal







CMS was dispersed uniformly in the matrix, while the CMC did not form a percolation structure (electrical contact).

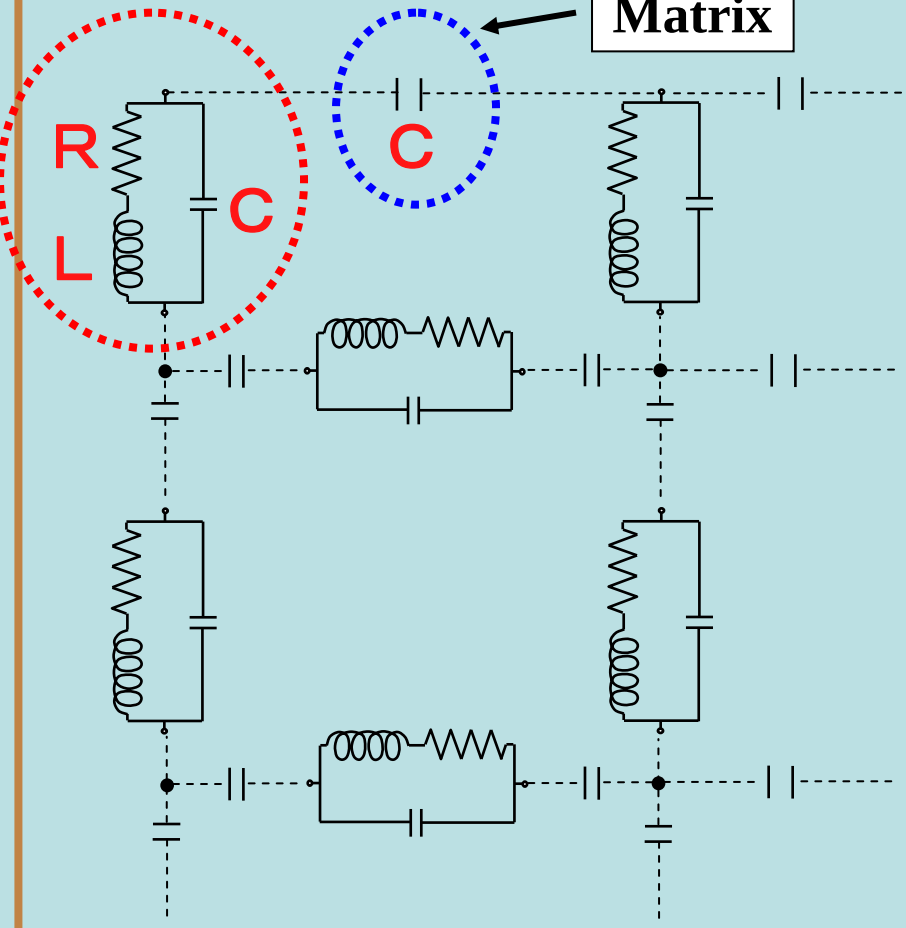
Possible tactile sensing mechanism of CMC sensor element

(Formation of Complex Electric Equivalent Circuit)

CMC

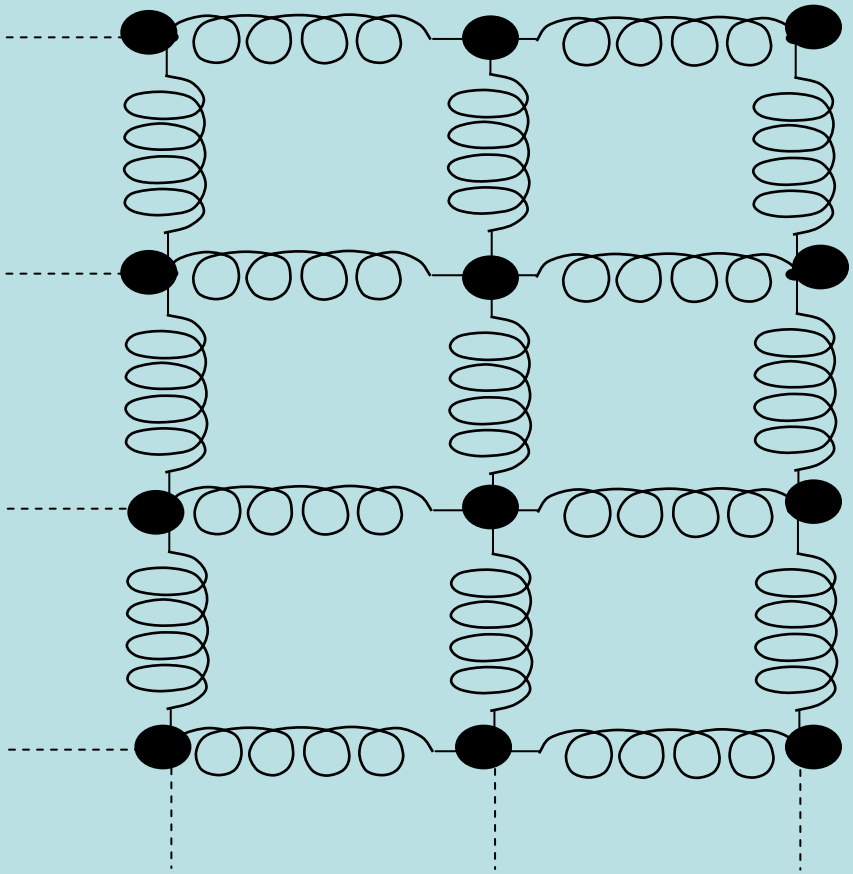
Electric Equivalent Circuit

Matrix



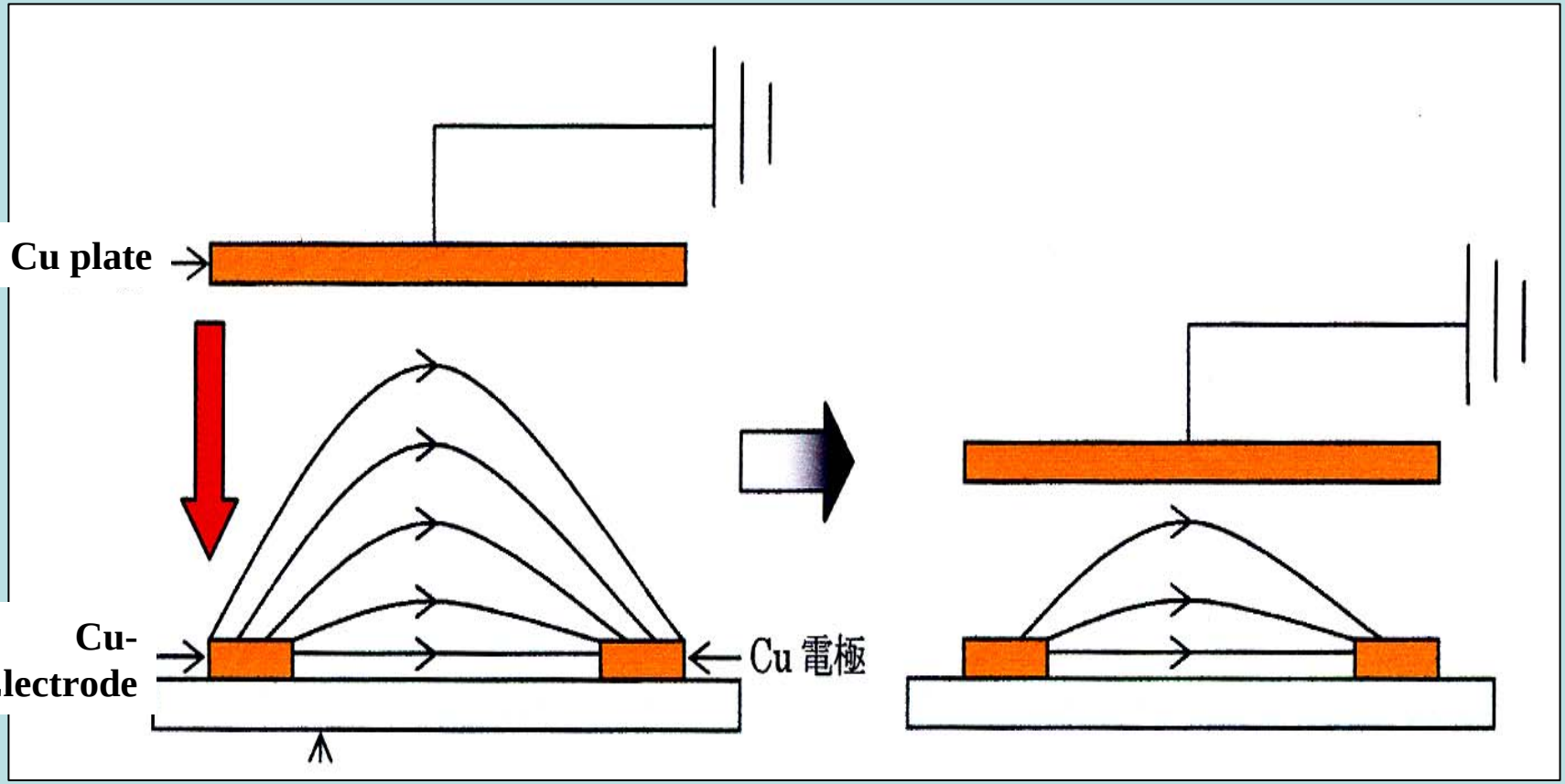
(LCR Complex Resonance Circuit)

Mechanical Dynamic Model

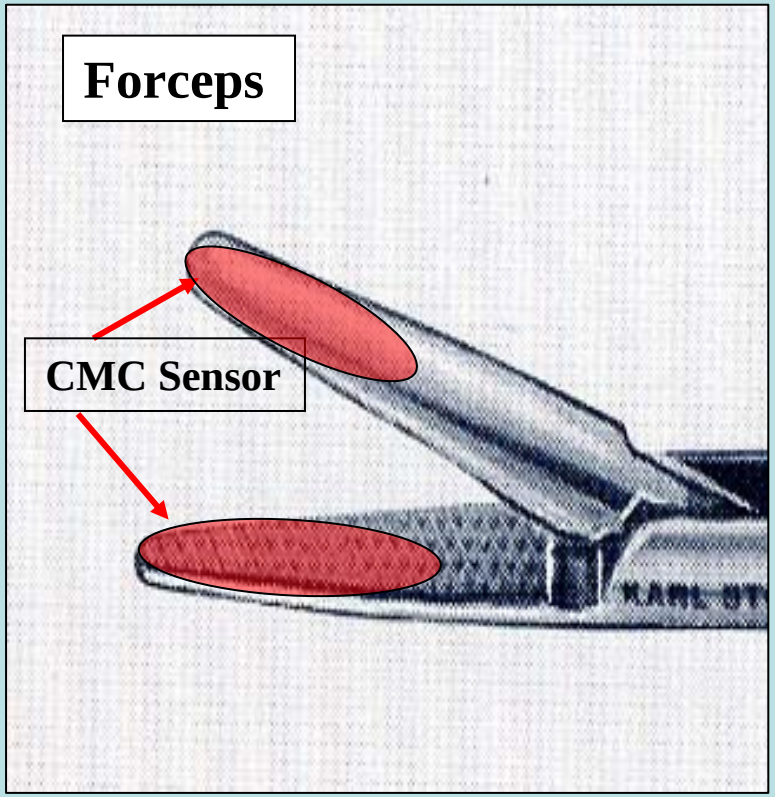


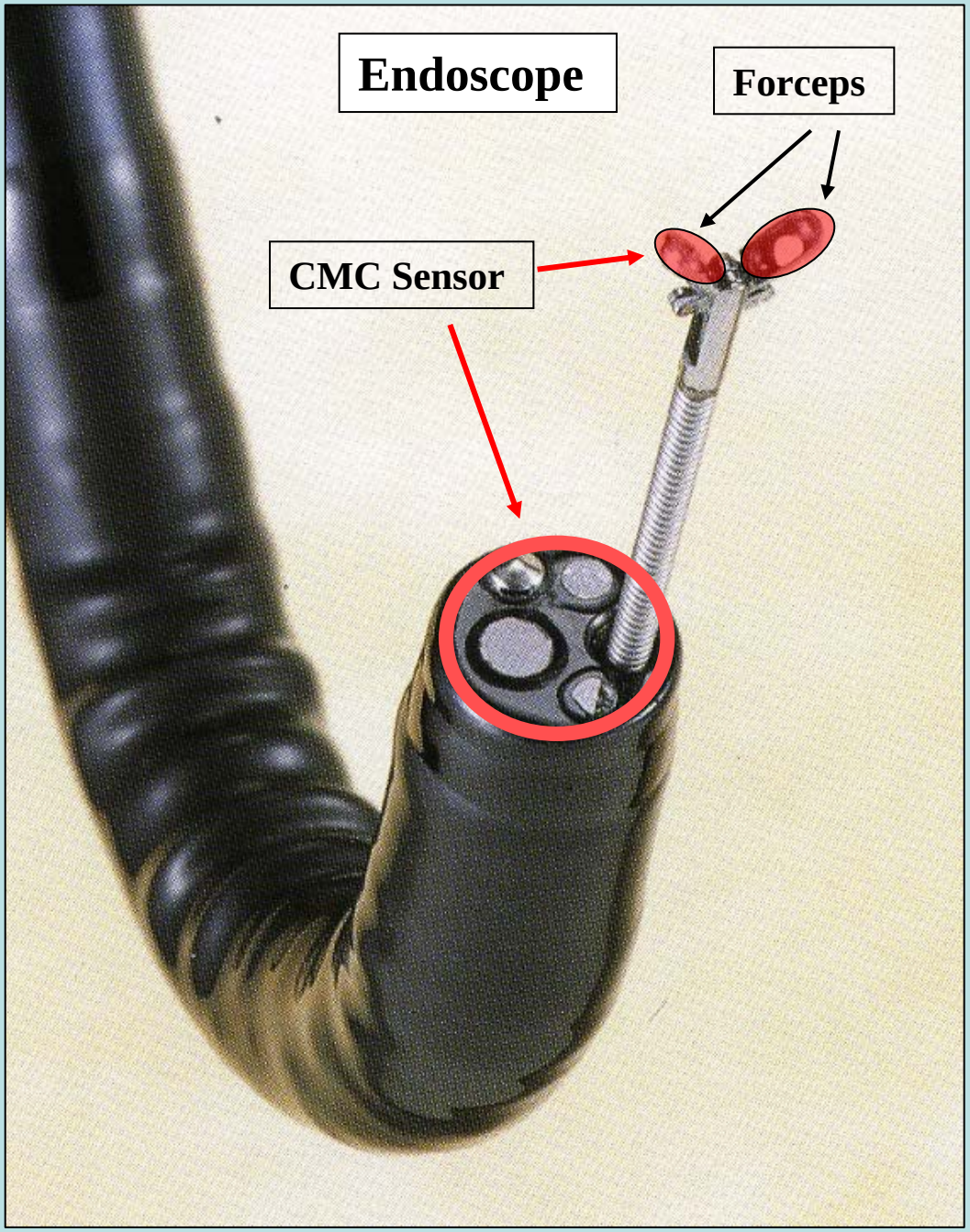
(Spring Material Point Model)

Possible proximity sensing mechanism of CMC sensor element
(Changing in space capacitance by accessing conductive substances)

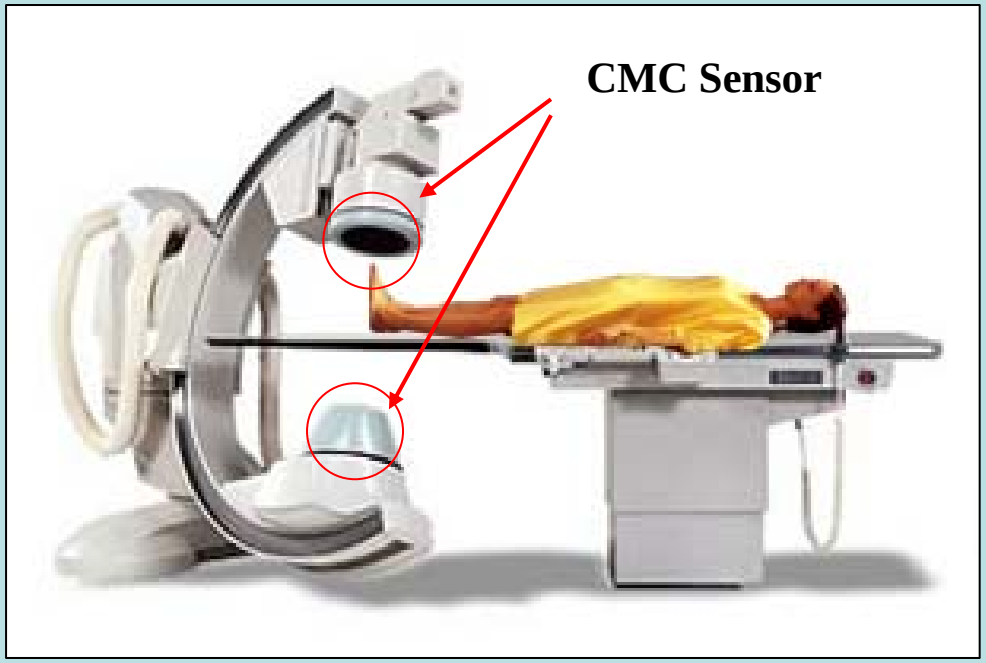


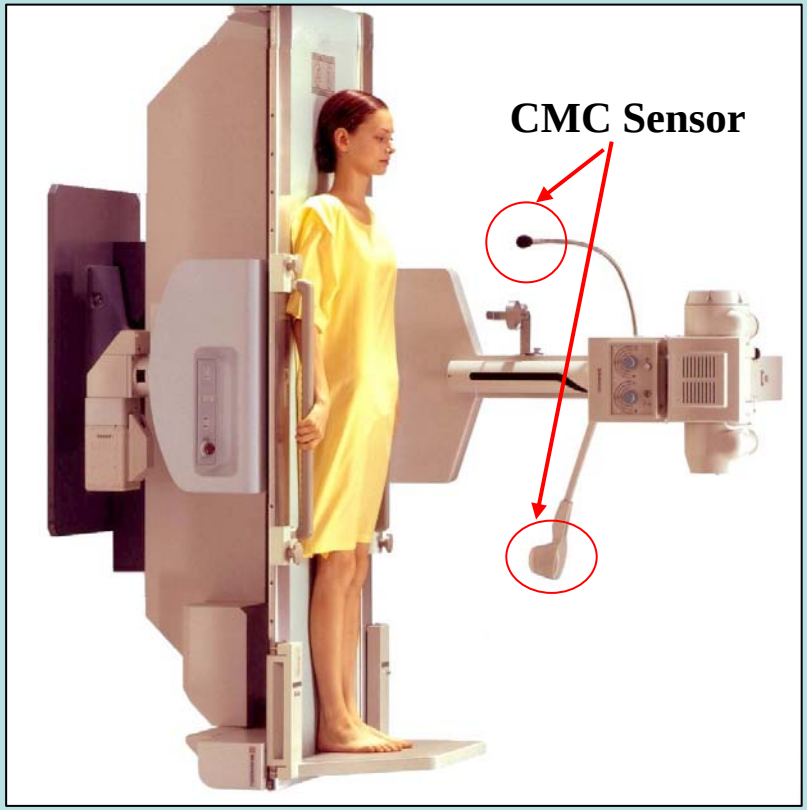
Applications to medical instruments for low invasive surgery





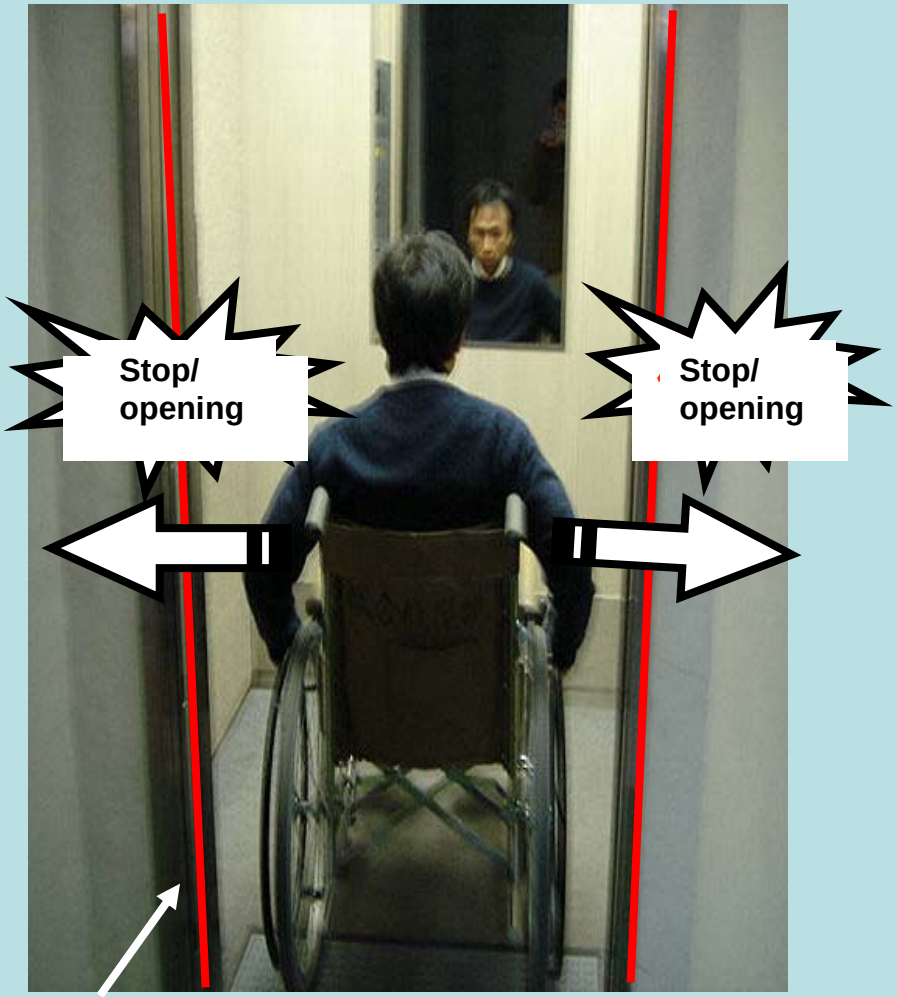
Application to the advanced medical instruments



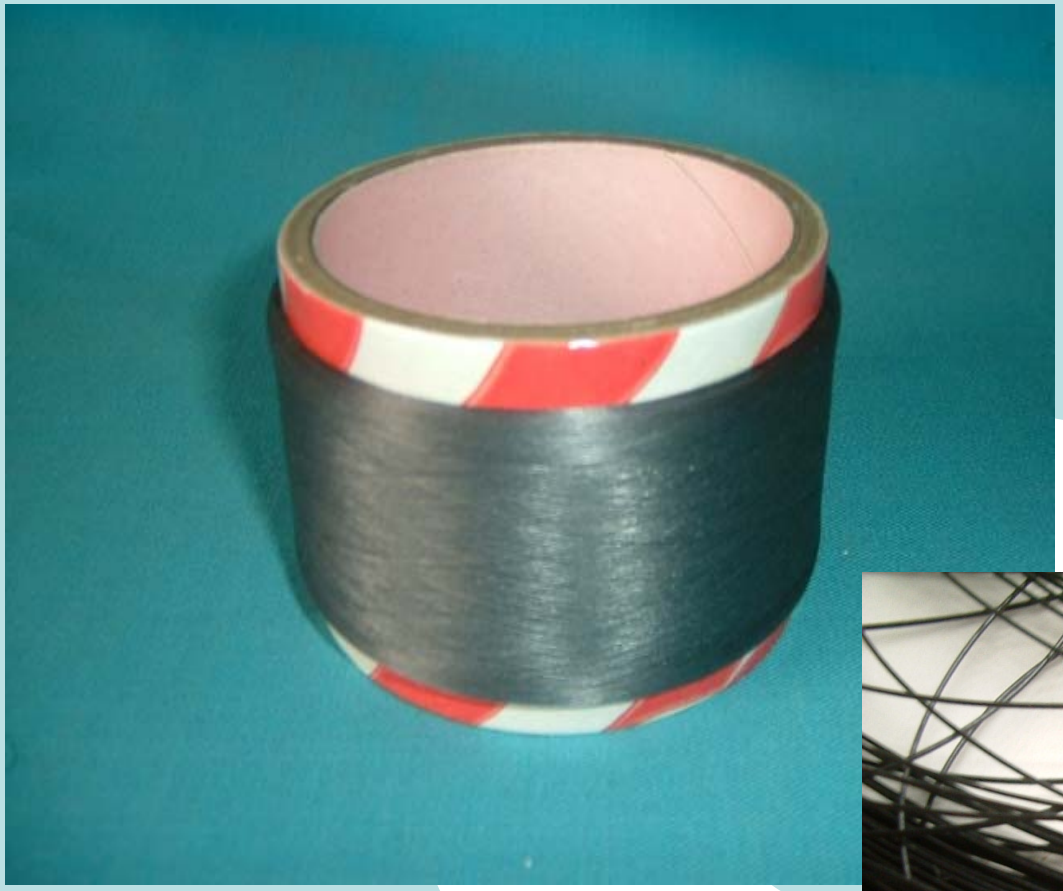


X-ray Diagnostic Instruments

Application to safety rotary door or elevator's door



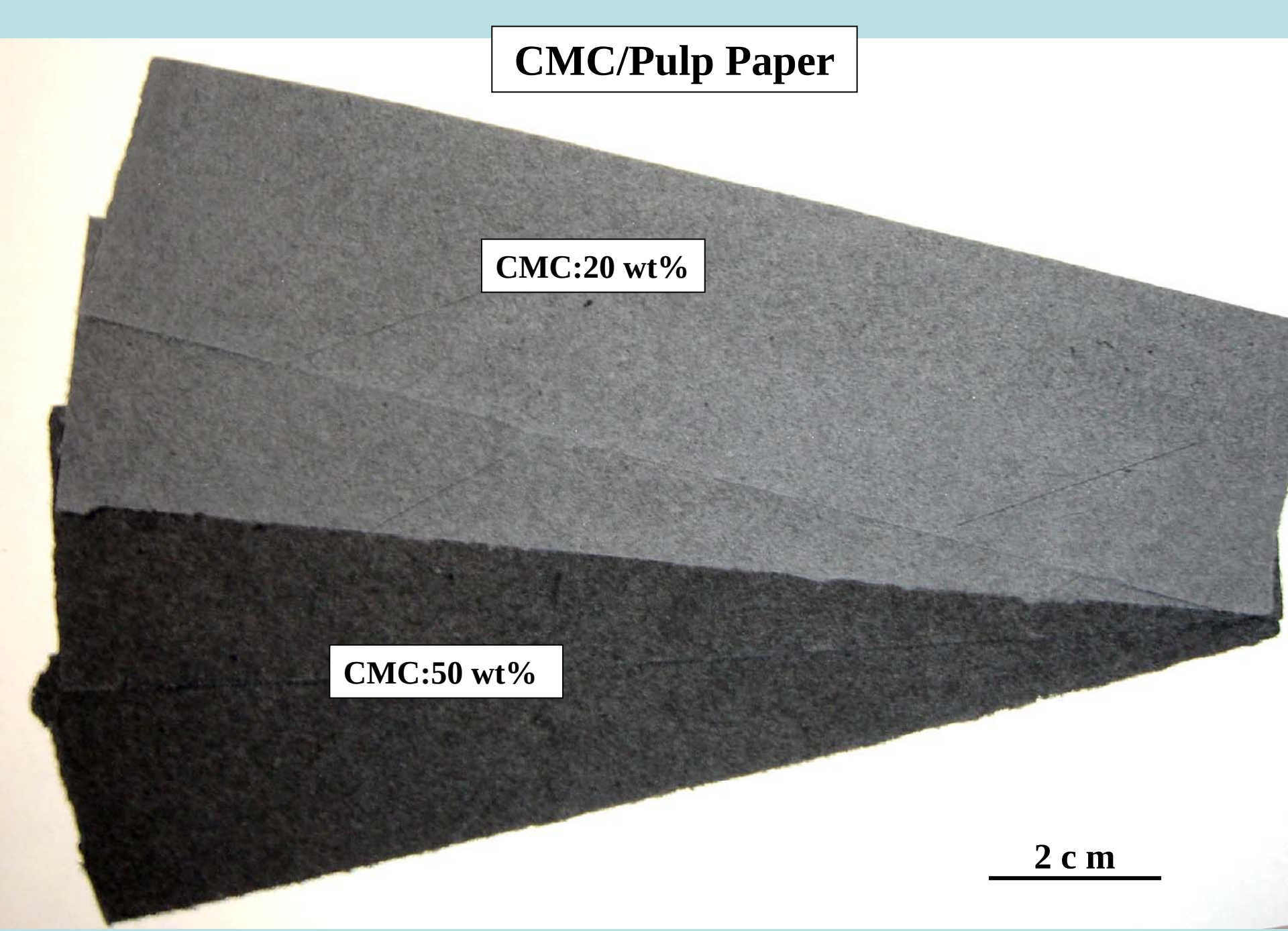
Red line indicates CMC sensor element



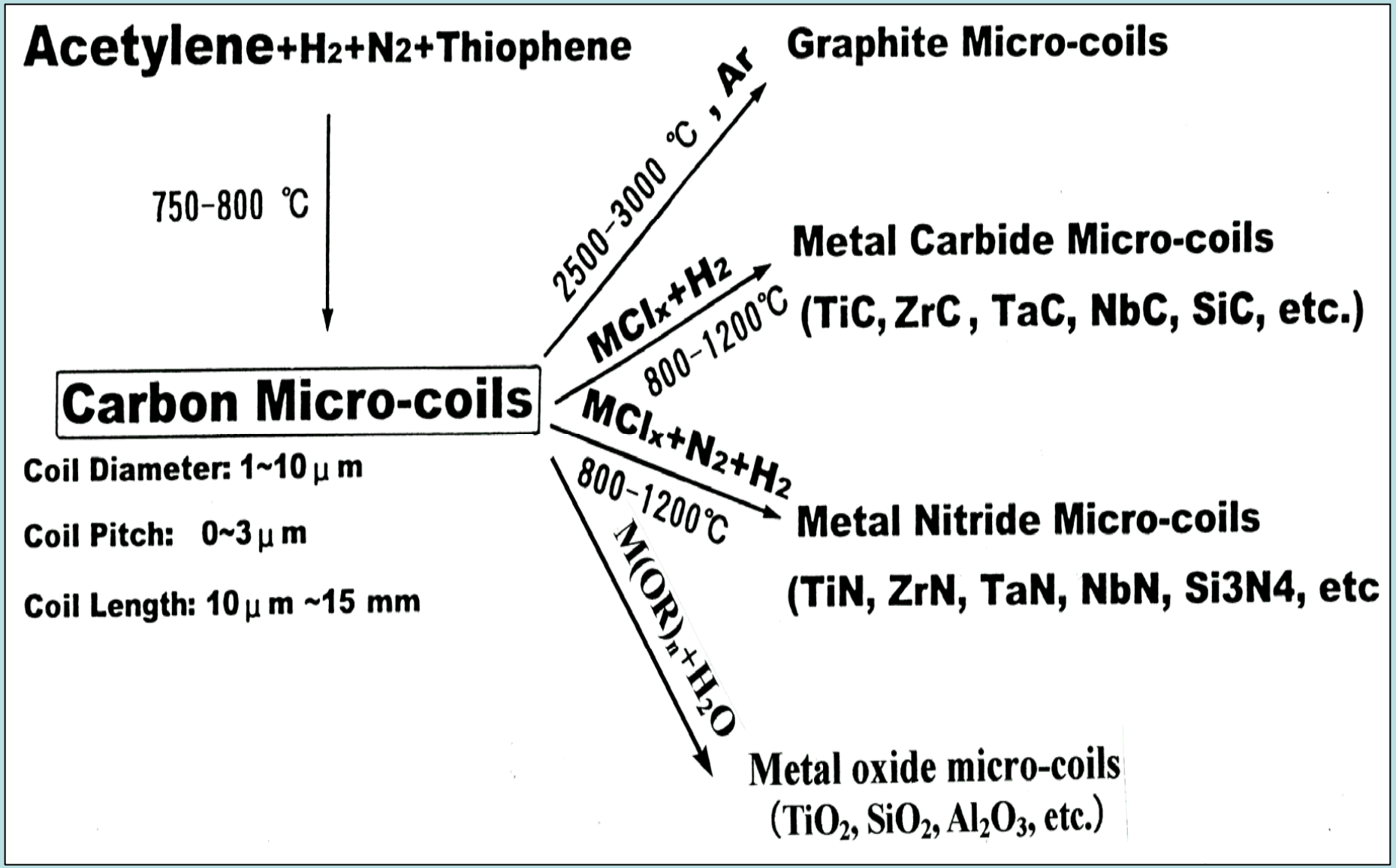
CMC-Containing Fibers

CMC / Polyurethane fibers

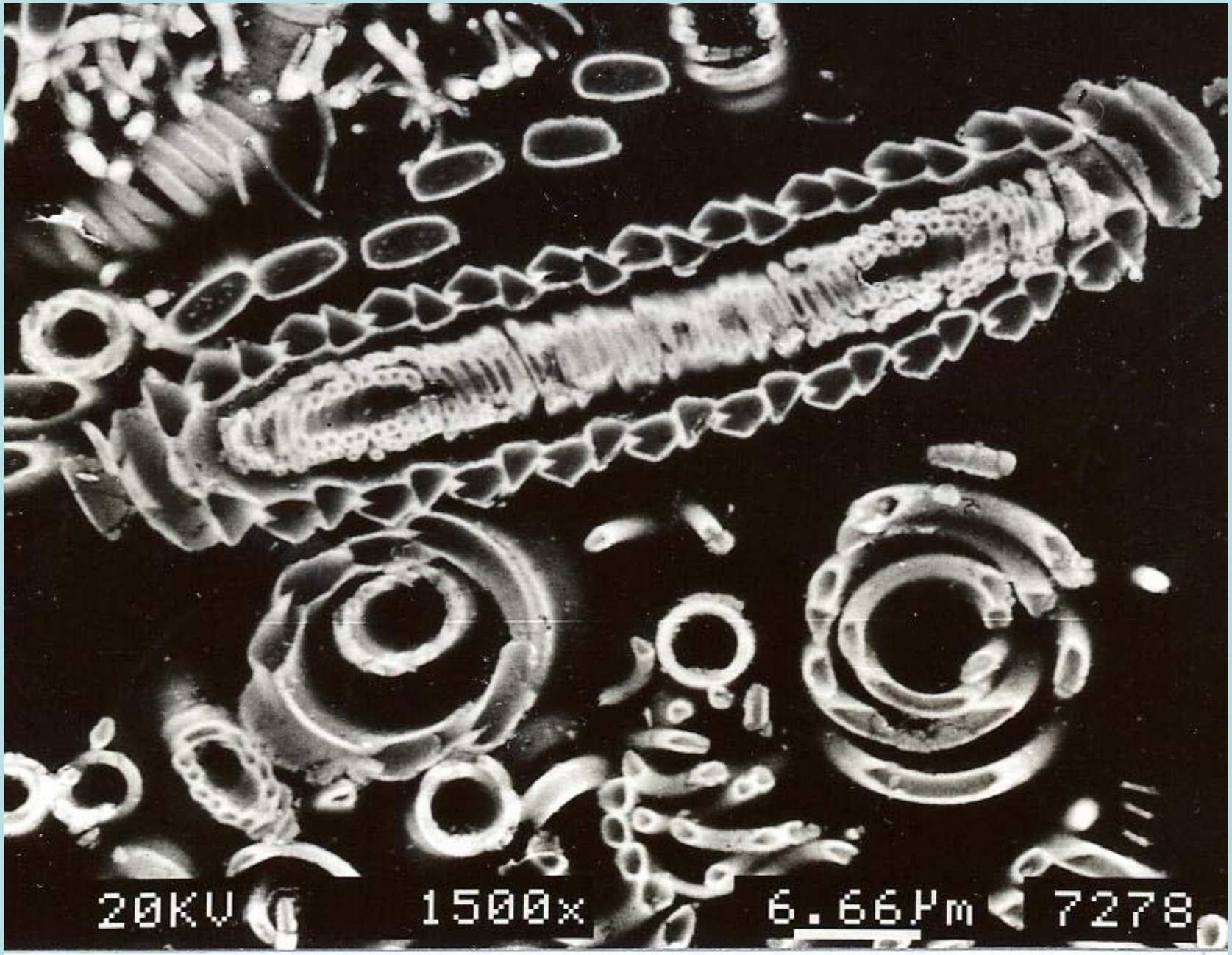
CMC/Pulp Paper



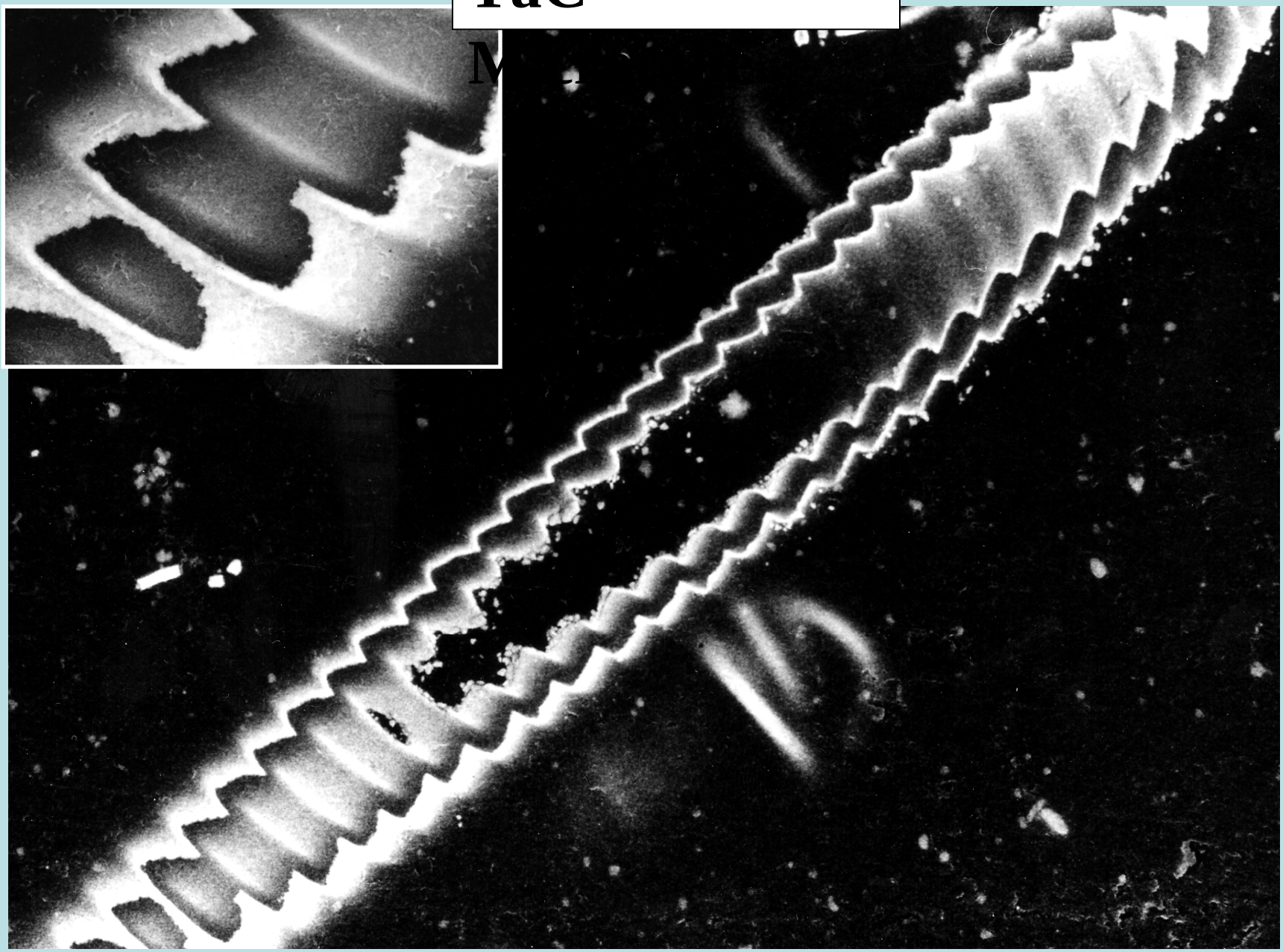
Preparation of Ceramic Microcoils/microtubes using CMC as a Template (by the high temperature vapor phase diffusion process)



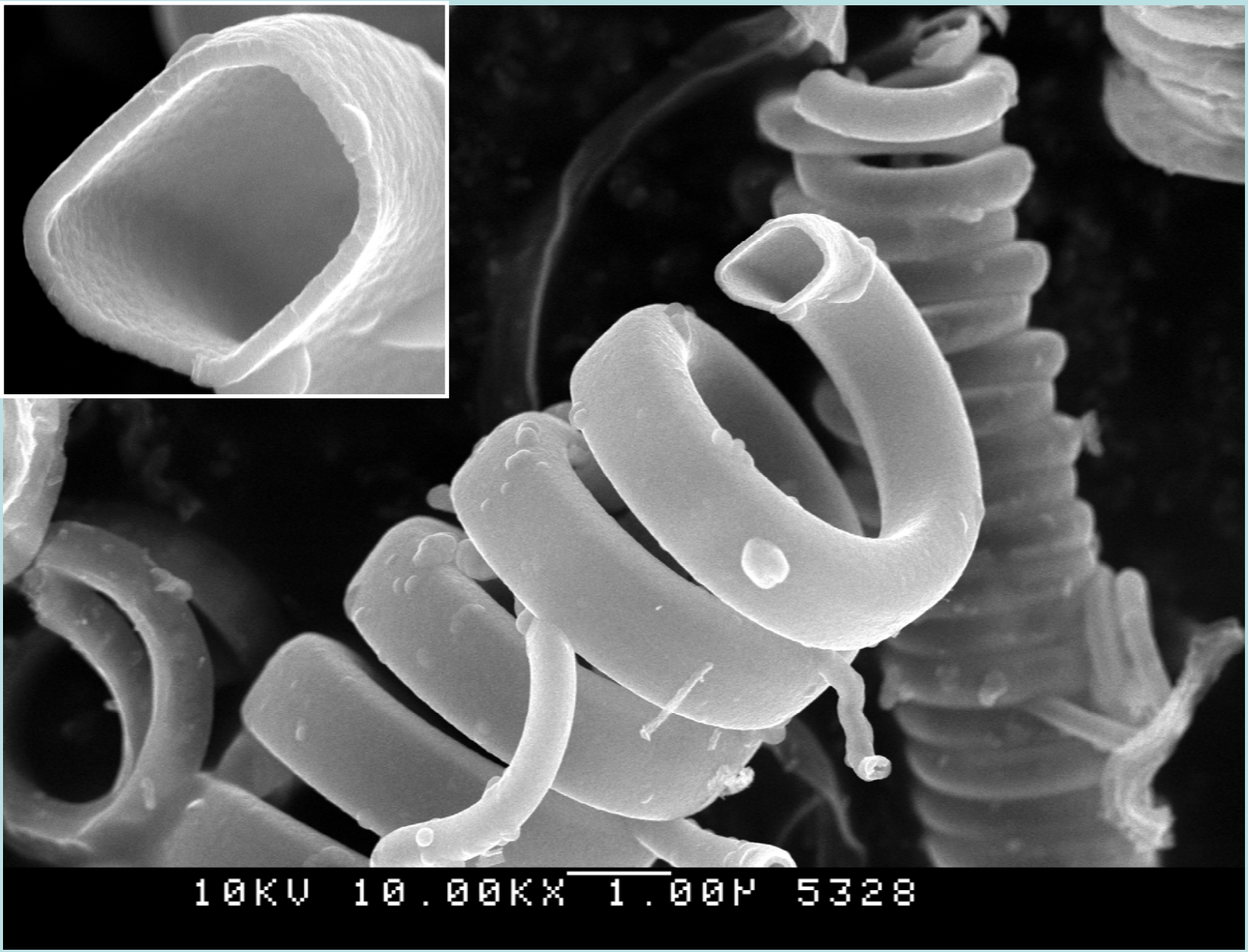
TiC/CMC Microcoils



TaC



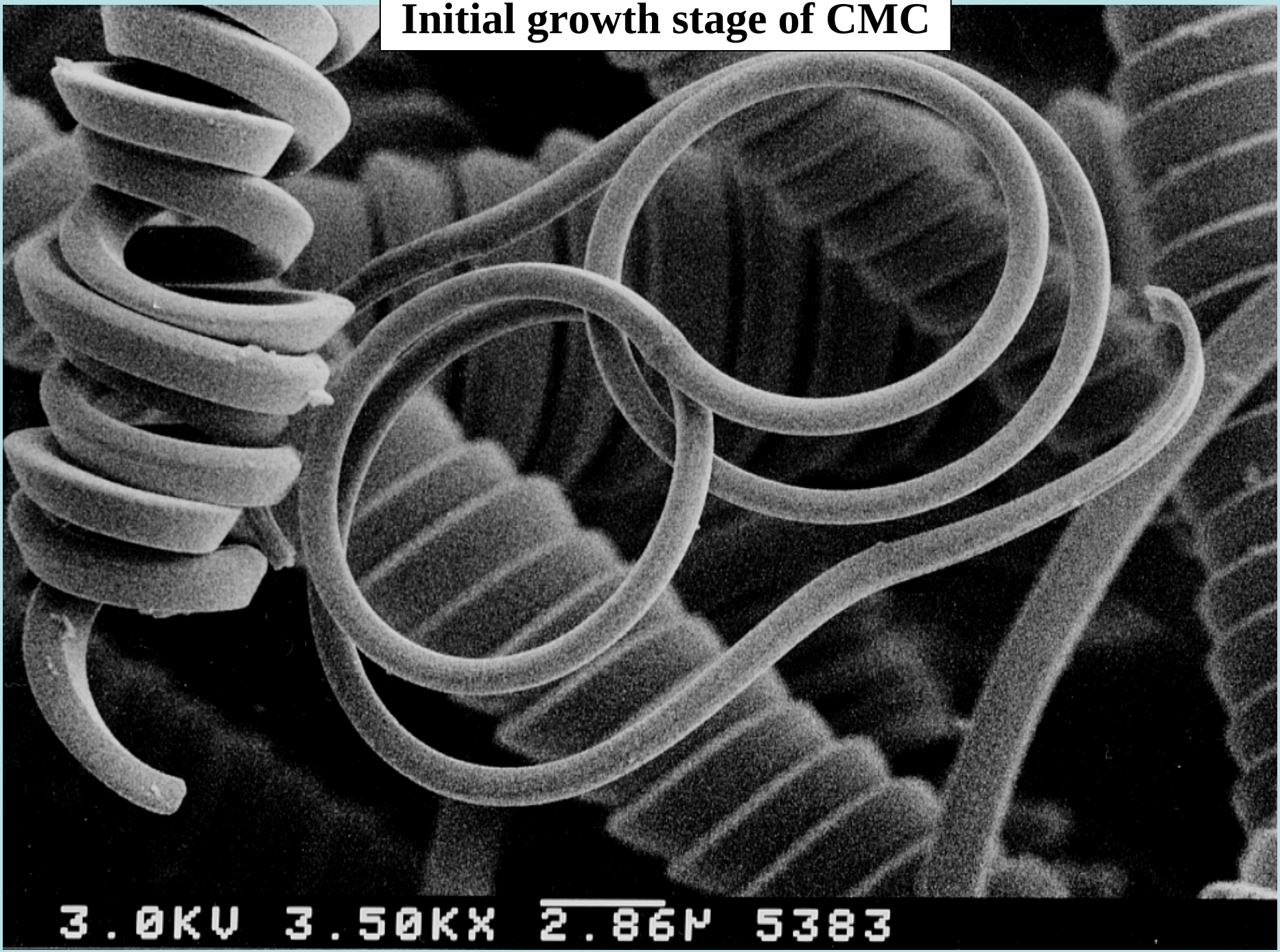
TiO_2 microcoil

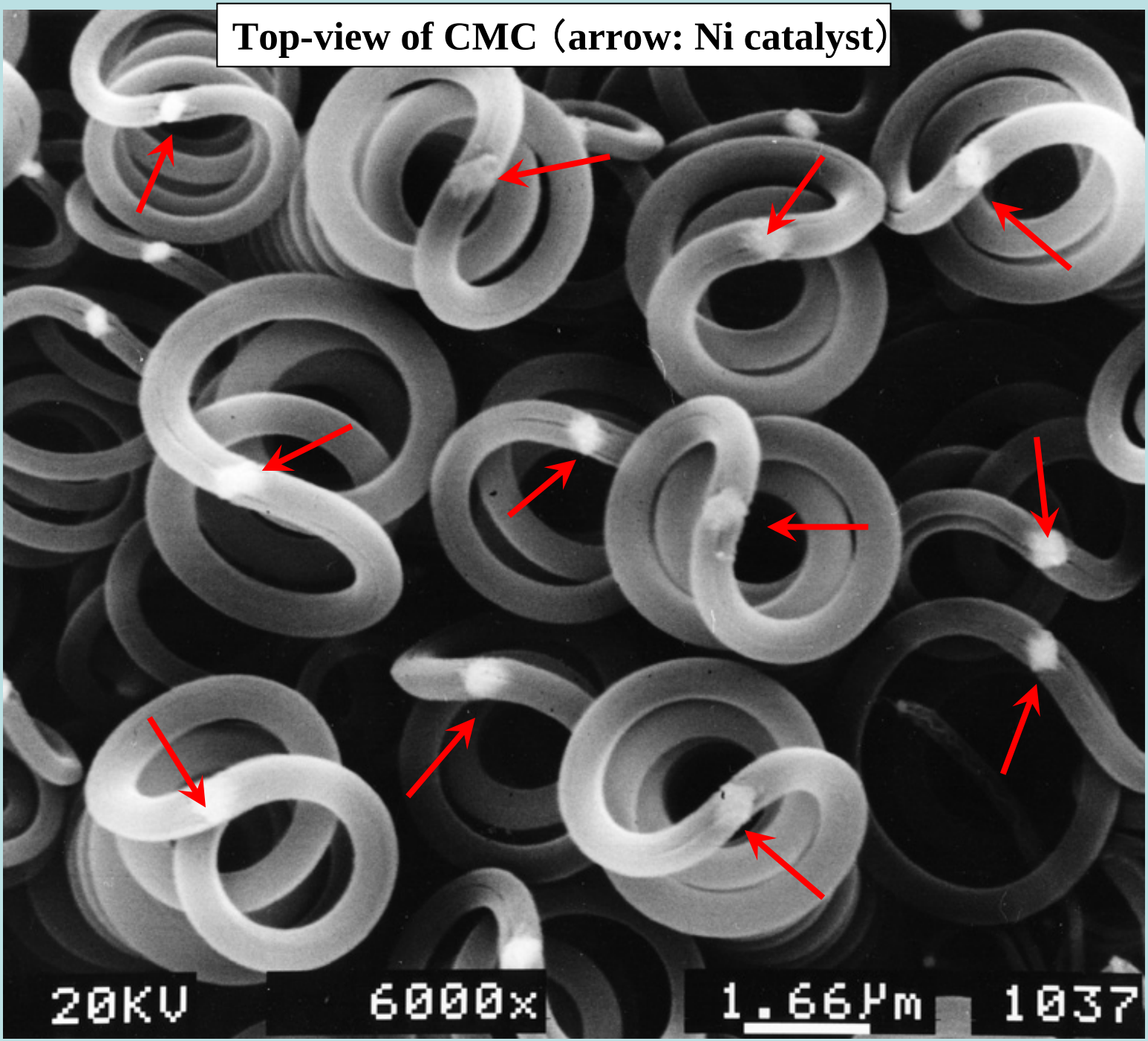


Application of Carbon Microcoils

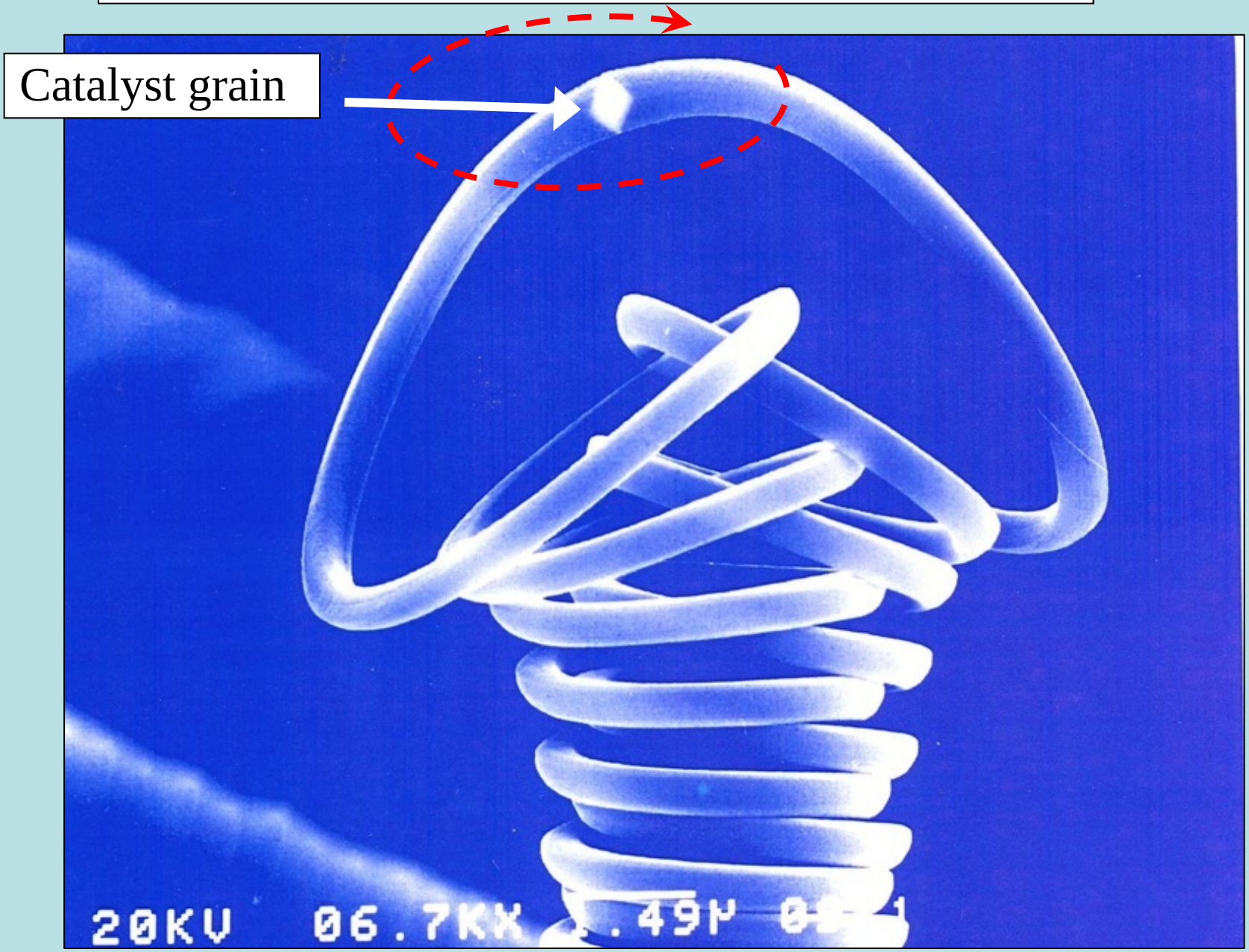
1	Electromagnetic absorbers	(1) Beads (2) Foams (3) Ceramic beads (4) Super-thin EM absorbers
2	Tactile sensors	(1) Medical sensors (2) Humanoid robot sensors (3) Artificial skins with tactile sensing properties (4) Aerospace sensors (5) Industrial sensors
3	Bio-activators	(1) Breeding or activating catalysts for skin cells, collagen fibrils, microorganisms, etc. (2) Activators of metabolism (3) Tissue engineering
4	Micro-antenna	(1) Micro-antenna for aerospace (2) Energy converters
5	Remote-heaters	(1) Remote micro-heaters (2) Micro-heaters for DDS
6	Others	(1) Super-elastic conductors (2) CMC containing fibers (3) etc.

Initial growth stage of CMC

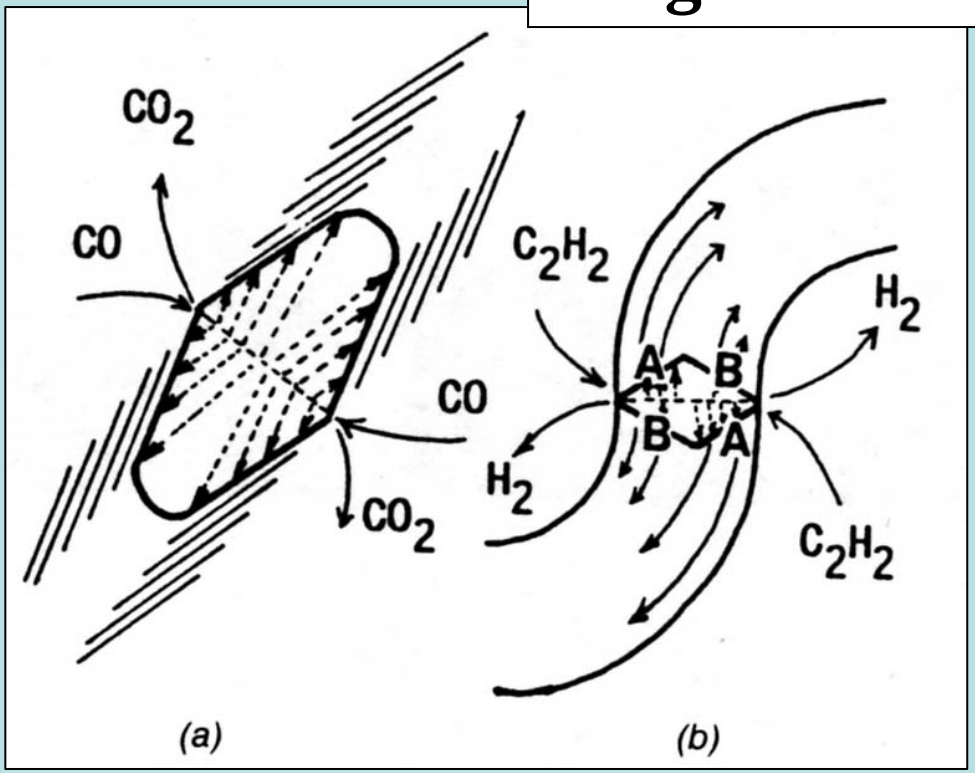



Top-view of CMC（arrow: Ni catalyst）
20KV
6000x
1.66μm
1037

Side-view of CMC (arrow: Ni_3C single crystal)



2D-growth model of CMC



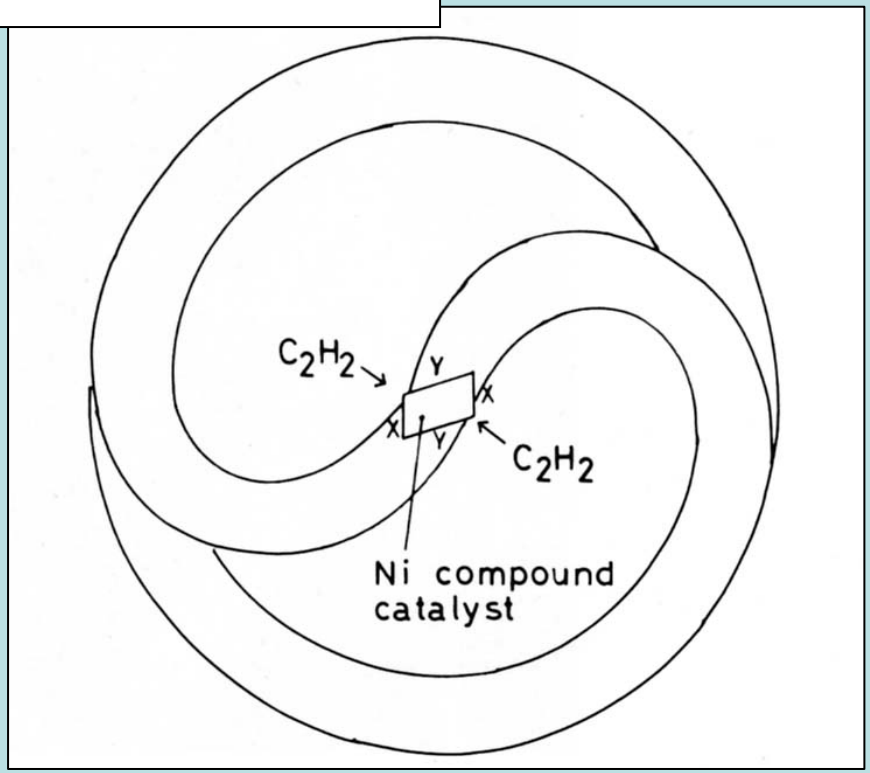


Table 4. Effects of Ni catalysts (single- and poly-crystals) on the deposition rate of total carbon and coil yield

Catalysts	Ni single-crystal plate			Ni poly-crystal plate
	Ni(100)	Ni(111)	Ni(110)	
Deposition rate of total carbon (mg/cm^2)	32	23	19	23
Coil Yield (mol%)	10.2	6.7	3.2	4.8

Coiling mechanism based on the anisotropic property of catalyst grain