FRONTIER LAB

Synthetic/biopolymer grinding applications using IQ MILL-2070 (Ver. 1.5)

Cryogenic Mill
IQ MILL-2070

List of grinding applications for synthetic polymers

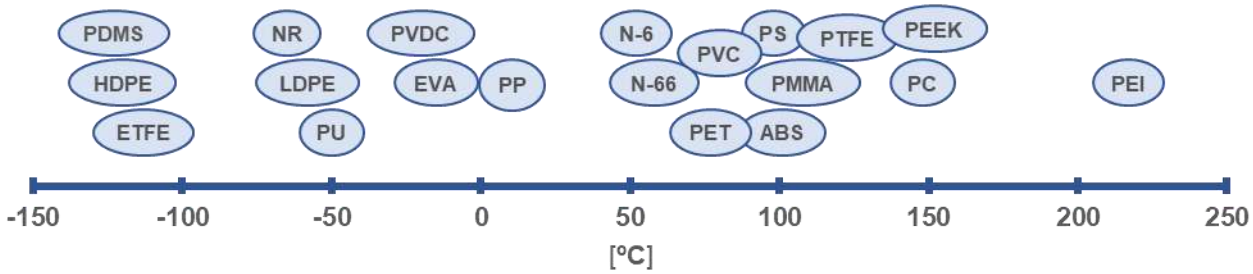
(Ver. 1.4)

Use the numbers to bring you straight to the corresponding page.

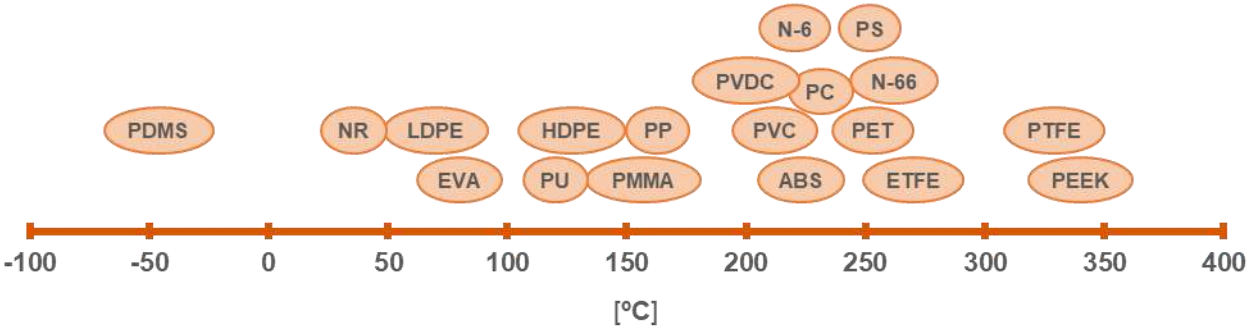
Synthetic polymers		
No.	Sample name	Abbrev.
IQ MILL_Poly_001	High density polyethylene	HDPE
IQ MILL_Poly_002	Low density polyethylene	LDPE
IQ MILL_Poly_003	Polypropylene	PP
IQ MILL_Poly_004	Polystyrene	PS
IQ MILL_Poly_005	Polycarbonate	PC
IQ MILL_Poly_006	Polyvinyl chloride	PVC
IQ MILL_Poly_007	Polyvinylidene chloride	PVDC
IQ MILL_Poly_008	Acrylonitrile butadiene styrene copolymer	ABS
IQ MILL_Poly_009	Silicone rubber	PDMS
IQ MILL_Poly_010	Polymethyl methacrylate	PMMA
IQ MILL_Poly_011	Polyisoprene (natural rubber)	NR
IQ MILL_Poly_012	Ethylene-vinyl acetate copolymer	EVA
IQ MILL_Poly_013	Polyethylene terephthalate	PET
IQ MILL_Poly_014	Polytetrafluoroethylene	PTFE
IQ MILL_Poly_015	Ethylene tetrafluoroethylene copolymer	ETFE
IQ MILL_Poly_016	Nylon 6	N-6
IQ MILL_Poly_017	Nylon 6,6	N-66
IQ MILL_Poly_018	Polyurethane	PU
IQ MILL_Poly_019	Polyetheretherketone	PEEK
IQ MILL_Poly_020	Polyetherimide	PEI

< 20 typical synthetic polymers >

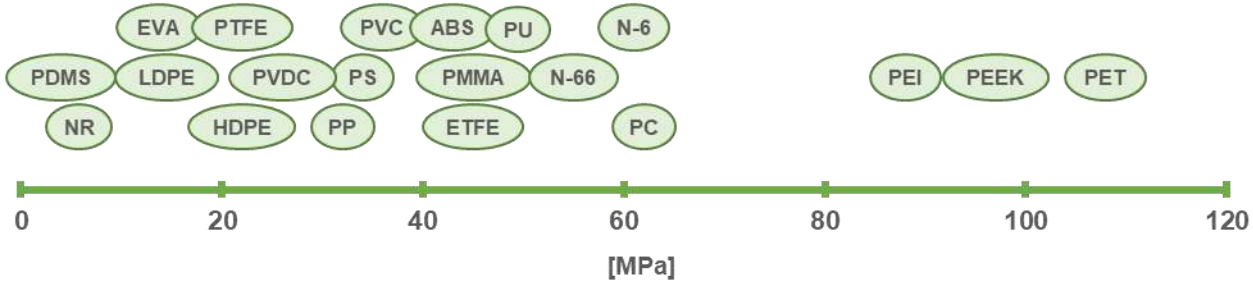
Glass transition temperature [Tg]



Melting point [Mp]



Tensile strength [TS]



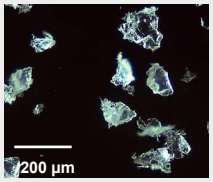
List of grinding applications for synthetic polymers

(Ver. 1.4)

Use the numbers to bring you straight to the corresponding page.

Synthetic polymers		
No.	**Sample name**	**Abbrev.**
IQ MILL_Poly_021	Copy paper	Paper
IQ MILL_Poly_022	Electronic circuit boards	Board
IQ MILL_Poly_023	Foamed polystyrene	PS
IQ MILL_Poly_024	Polyethylene (PE) form	PE
IQ MILL_Poly_025	Low density polyethylene film	LLDPE
IQ MILL_Poly_026	Polyamide fiber	PA
IQ MILL_Poly_027	Nitril glove	-
IQ MILL_Poly_028	Styrene-butadiene rubber	SBR
IQ MILL_Poly_029	Cardboard	-

Application example

No.	Sample name (Abbrev.) Sample amount	Before	Conditions	After	Photomicrograph
IQ MILL_Poly_002	Polyethylene (LDPE) 0.48 g		3000 rpm x 30 sec Cryogenic grinding x 2 cycles		

List of grinding applications for biopolymers

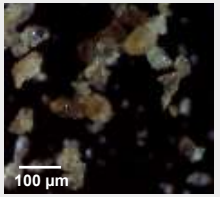
(Ver. 1.4)

Use the numbers to bring you straight to the corresponding page.

Biopolymers	
No.	**Sample name**
IQ MILL_Bio_001-1	Boar canines (Teeth)
IQ MILL_Bio_001-2	Fox, raccoon, raccoon dog (Teeth)
IQ MILL_Bio_002	Shellfish
IQ MILL_Bio_003	Bark of moso bamboo
IQ MILL_Bio_004	Hemp cord
IQ MILL_Bio_005	Wood chip
IQ MILL_Bio_006	Cotton
IQ MILL_Bio_007	Dried squid
IQ MILL_Bio_008	Beef jerky
IQ MILL_Bio_009	Shell string
IQ MILL_Bio_010	Sea squirt

Biopolymers	
No.	**Sample name**
IQ MILL_Bio_011	Seaweed stem (Wakame)
IQ MILL_Bio_012-1	Almond seed (Shell)
IQ MILL_Bio_012-2	Almond seed (Edible part)
IQ MILL_Bio_013	Candy
IQ MILL_Bio_014	Leaves of houseplants

Application example

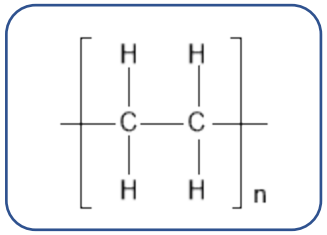
No.	Sample name Sample amount	Before	Conditions	After	Photomicrograph
IQ MILL_Bio_012-1	Almond seed (shell) 0.93 g		3000 rpm x 30 sec Room temp. grinding x 1 cycle		

High density polyethylene (HDPE) [Cryomilling]

IQ MILL_Poly-001

Characteristics: HDPE or PE-HD is a crystalline thermoplastic resin consisting of linearly bonded repeating units of ethylene with few branches. It is also called rigid polyethylene because of its hardness compared to other polyethylene (PE).

Application: Films and sheets such as shopping bags, blue sheets, etc., also fibers that have been strengthened by stretching (fishnets, screen doors, leisure sheets, etc.).



Schematic of molecular structure of HDPE

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.48	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions[1]
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
2500/3000	20	20	2	3

HDPE 0.48 g

Pretreatment: Cut in half with nippers

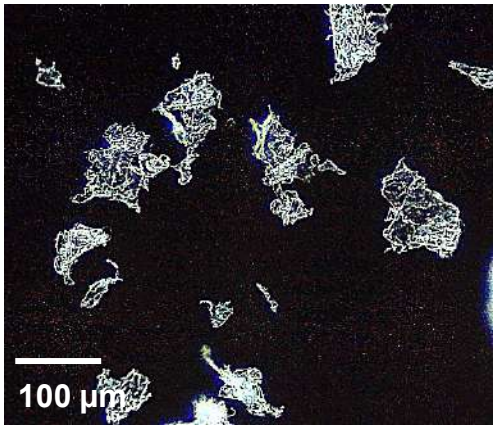
Grinding conditions: 2500 rpm

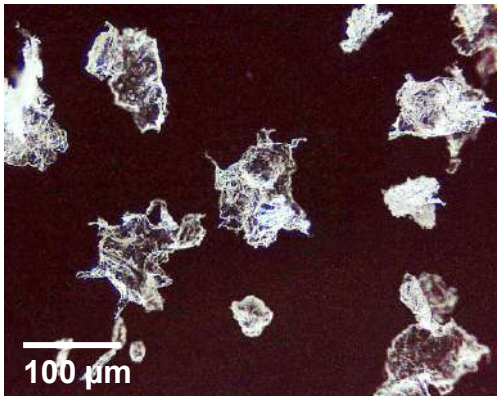
(<40 mesh[2], Yield: 55 %)

Grinding conditions: 3000 rpm

(<40 mesh, Yield: 68 %)

Ground to a particle size of approx. 100 µm





1) Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

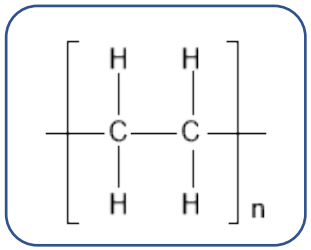
2) 40 mesh= 0.42 mm opening

Low density polyethylene (LDPE) [Cryomilling]

IQ MILL_Poly-002

Characteristics: Low density polyethylene (LDPE) is a synthetic resin consisting of randomly branched repeating units of ethylene. It is also called soft polyethylene because of its softness compared to other polyethylenes, or high-pressure polyethylene because of its manufacturing process.

Application: Packaging materials (simple packaging for confectionery and clothing, garbage bags, packaging for fresh food, cushioning materials), black agricultural film, sanitary gloves, watering hoses, Tupperware, etc.



LDPE 0.48 g

Schematic of molecular structure of LDPE

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.48	Cryogenic	Sample container L-Ti	WC-10Φ/12Φ

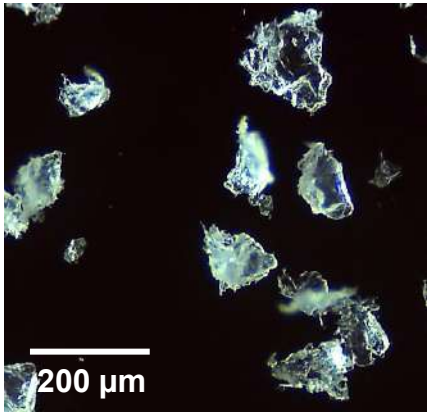
Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
2500/3000	30	20	2	1

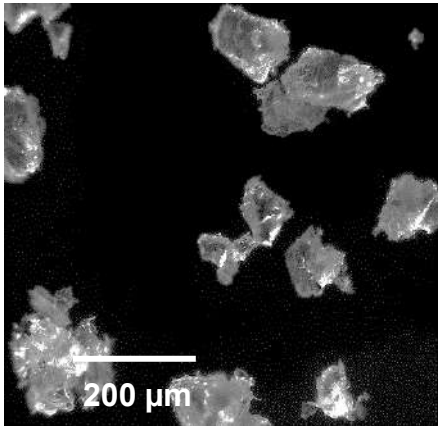
Grinding ball: WC-10Φ

Grinding ball: WC-12Φ

Ground to a particle size of approx. 100-200 μm (<40 mesh, yield: 85 %)



Ground to a particle size of approx. 100-200 μm (<40 mesh, yield: 78 %)

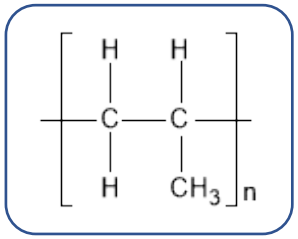


* 40 mesh= 0.42 mm opening

Polypropylene (PP) [Cryomilling]

Characteristics: Nylon 6,6 is a polyamide with higher heat resistance and mechanical strength than nylon 6, with a melting point around 265 ºC and specific gravity of 1.14. It is one of the strongest materials among engineering plastics. In addition to heat resistance, it has excellent oil resistance, wear resistance, and lubricating properties.

Application: Textiles for clothing, airbags, bearings, liners, rollers, gears, insulating parts, etc.



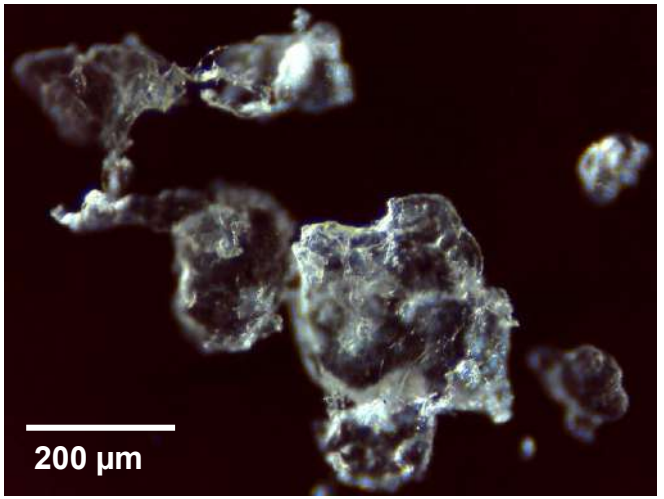
PP 0.61 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.58	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	2	1

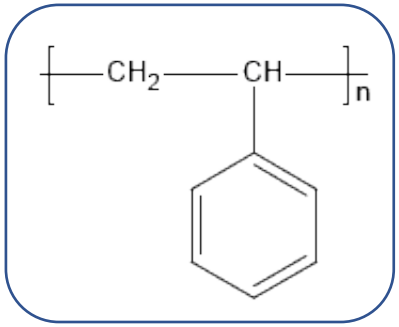
Ground to a particle size of about 100-200 µm
(<40 mesh, yield: 88 %)



*40 mesh= 0.42 mm opening

Polystyrene (PS) [Cryomilling /room temp. dry/room temp. wet]

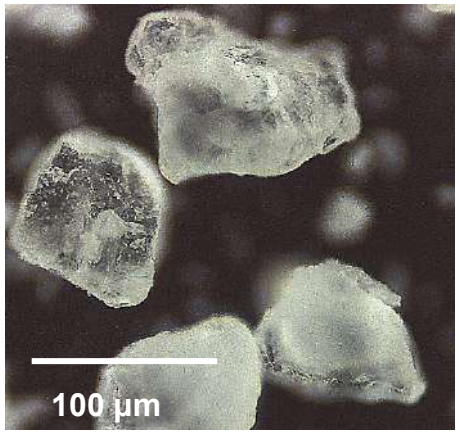
IQ MILL_Poly-004



PS 1.0 g

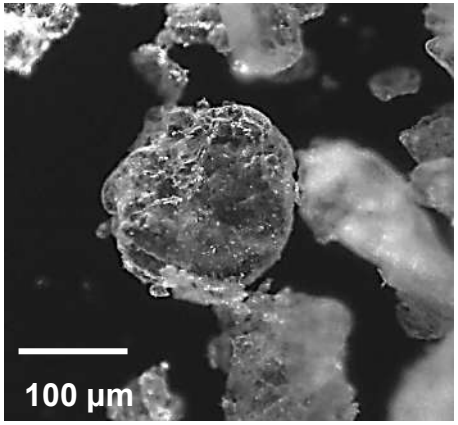
Cryogenic grinding (-196 ºC)

Grinding time: 30 sec Pause: 10sec
No. of cycles : 2 Repetition: 1
Yield (> 40 mesh : 0 %)
(40-60 mesh : 4.8 %)
(< 60 mesh : 95.2 %)



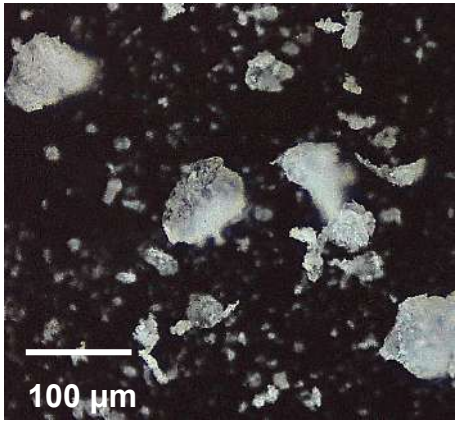
Room temp. dry (23 ºC)

Grinding time: 30 sec Pause: 60sec
No. of cycles : 10 Repetition: 2
Yield (> 40 mesh : 6.0 %)
(40-60 mesh : 19.3 %)
(< 60 mesh : 74.7 %)



Room temp. wet (23 ºC, methanol 1.5 mL)

Grinding time: 30 sec Pause: 60sec
No. of cycles : 10 Repetition: 2
Yield (> 40 mesh : 0.2 %)
(40-60 mesh : 5.4 %)
(< 60 mesh : 94.4 %)



1) 40 mesh= 0.42 mm opening, 60 mesh= 0.25 mm opening

- In cryogenic grinding, the particle size is about 100 µm.
- In room temperature dry grinding, the particle size is mainly about 100 µm. (The particles cannot be smaller than this due to aggregation caused by static electricity.)
- In room temperature dry grinding, the sample container and grinding ball heat is dissipated at Pause time of 60 sec, but when Pause time is 0 sec, the PS particles are heated by the impact of the sample container and the Grinding ball and clump together.
- In room temperature wet grinding with methanol, particles of 10 µm-50 µm were observed. This may be due to the relaxation of the charges between particles by methanol.

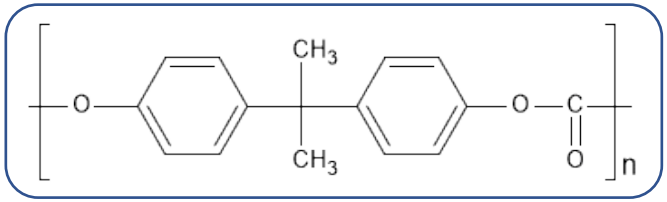
Sample amount (g)	Room temp./Cryogenic	Sample container	Grinding ball	Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	No. of repetitions[2)]
1.0	Room temp.(dry/wet) Cryogenic	Sample container L-Ti	Zr-12Φ	3000	30	60 / 10	10 / 1	2

2) Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

Polycarbonate (PC) [Cryomilling/Room temp. milling]

IQ MILL_Poly-005

Characteristics: Polycarbonate resin (PC) is an engineering plastic with high transparency, self-extinguishing properties, and the highest impact resistance of any plastic. With transparency comparable to that of glass, PC is also used in camera lenses.



PC 0.5 g

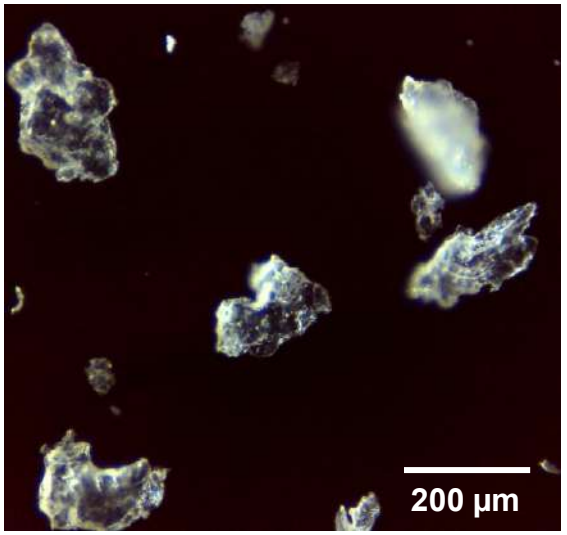
Pretreatment: cut in half with nippers

Cryogenic grinding

Room temp. grinding

(The same grinding conditions as Cryogenic grinding used. Although the sample was slightly ground, flat plates of about 0.2 mm in size were obtained. Also, the grinding ball became very hot.)

(<40 mesh[1)], yield: 80 %)



1) 40 mesh= 0.42 mm opening

- In room temperature grinding, the impact of the grinding ball causes to raise the PC temperature, making the sample flat in shape and impossible to grind.
- In cryogenic grinding, particles of about 200 µm in size can be obtained.

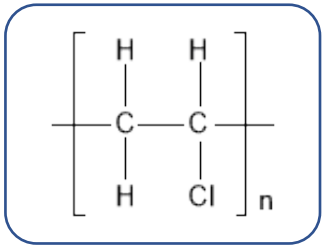
Sample amount (g)	Room temp./Cryogenic	Sample container	Grinding ball	Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	No. of repetitions[2)]
0.5	Room temp./Cryogenic	Sample container L-Ti	WC-12Φ	3000	30	10	10 / 2	2 / 1

2) Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

Polyvinyl chloride (PVC) [Cryomilling]

Characteristics: PVC (PVC) has excellent chemical resistance, corrosion resistance, and insulating properties, and is an inexpensive polymer among plastic materials. Although it is vulnerable to low and high temperatures, it is used in a wide range of applications because it is inexpensive for its many advantages.

Application: It is used for building materials such as water and sewage pipes and corrugated sheets, and leather for furniture. It is often found in familiar places.



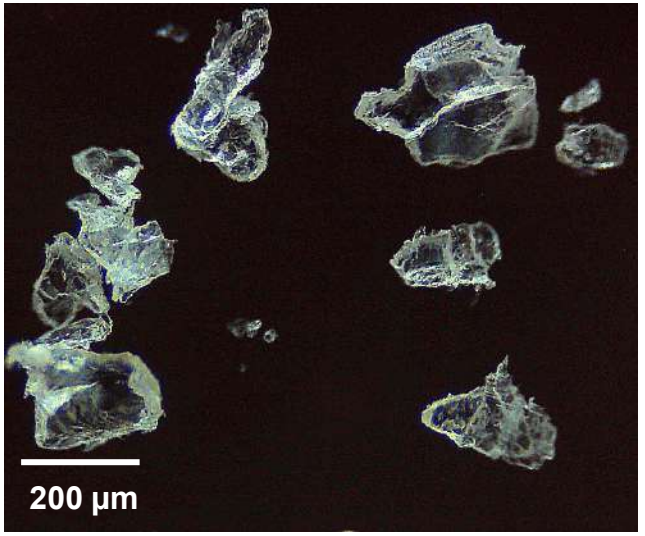
PVC thin plates 0.55 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.55	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
3000	20	-	1	-

(<40 mesh, yield: 100 %)

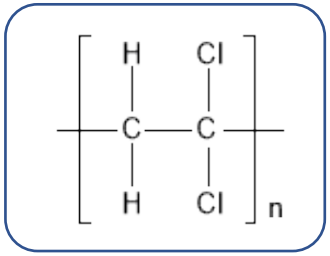


*40 mesh= 0.42 mm opening

Polyvinylidene chloride (PVDC) [Cryomilling]

Characteristics: Polyvinylidene chloride (PVDC) features high barrier to block both oxygen and moisture. This is an outstanding feature not found in other plastics and resins.

Application: Typical applications for PVDC include food packaging films such as wraps, ham, and sausages. Because of its excellent barrier properties, it can prevent unpleasant odors mixed with food odors from filling refrigerators and can also delay oxidation of wrapped foods to prolong the life of the foods. It also has a high heat and tear resistances.



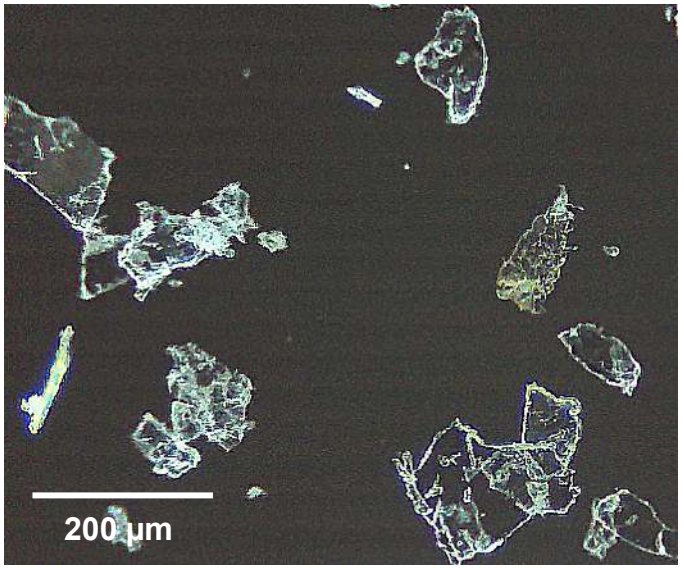
PVDC 0.38 g
(10 μm thick)

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.38	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
3000	30	-	1	-

(<40 mesh, yield: 100 %)



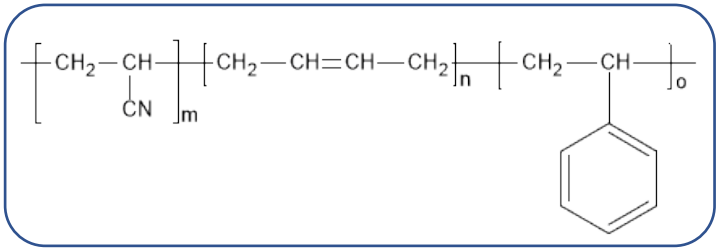
*40 mesh= 0.42 mm opening

Acrylonitrile-butadiene-styrene copolymer (ABS) [Cryomilling]

IQ MILL_Poly-008

Characteristics: ABS resin is a copolymer of acrylonitrile, butadiene, and styrene, and is a thermoplastic, amorphous general-purpose resin. The material color is light skin-colored, and it has an excellent balance of mechanical properties such as rigidity, hardness, workability, impact resistance, and bending fatigue.

Application: Mainly for various exterior, housing, and mechanical parts of home appliances and electrical and electronic products, interior parts such as automobile panels, stationery and miscellaneous goods, office furniture components, brush handles, etc.



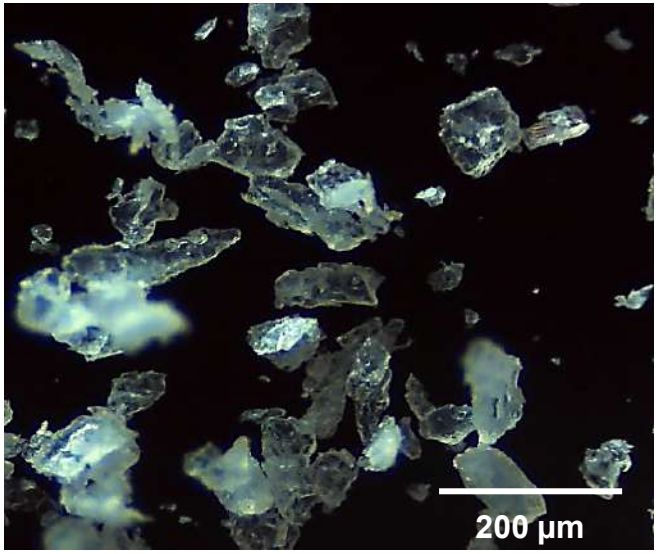
ABS 0.53 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.53	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	2	1

Ground to a particle size of approx. 100 µm (<60 mesh, yield: 91 %)

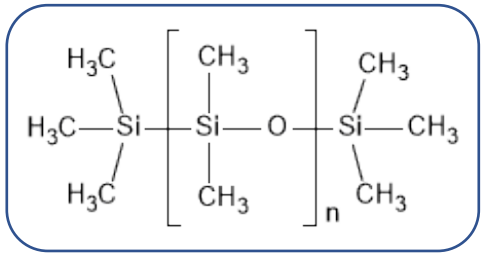


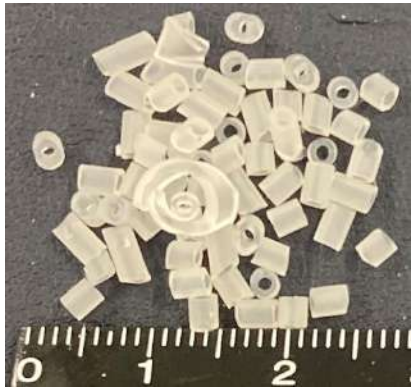
*60 mesh= 0.25 mm opening

Silicone resin (PDMS) [Cryomilling]

Characteristics: Silicone is a general term for synthetic polymer compounds that have a main skeleton of siloxane bonds. Generally, it is colorless, odorless, and has water repellency, and is oil resistant, oxidation resistant, and heat resistant compared to the corresponding carbon skeleton polymer. Since it has the properties of a metal oxide (base), it is weak against strong acids and easily deteriorates (bleaching, embrittlement).

Application: PDMS is used in a wide range of familiar and industrial applications, including contact lenses, medical devices, caulking agents, lubricants, and microfluidics.





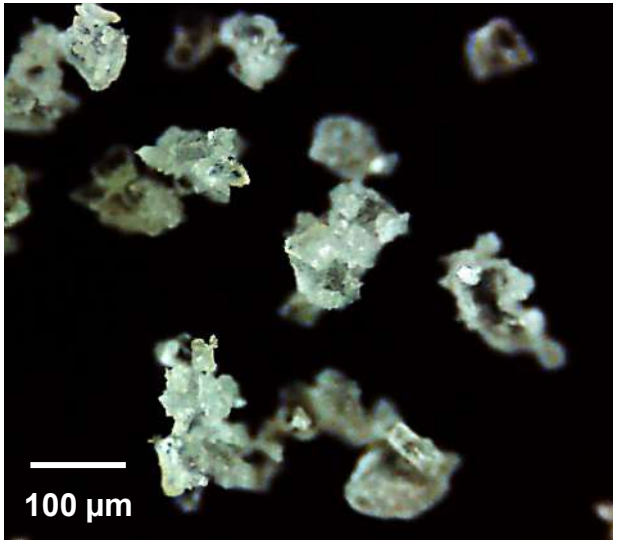
PDMS 0.55 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.55	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	20	20	2	1

Ground to a particle size of approx. 100 µm (<40 mesh, yield: 71 %)



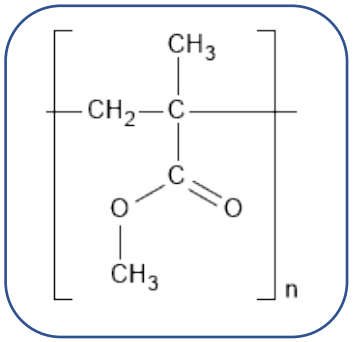
*40 mesh= 0.42 mm opening

Polymethyl methacrylate (PMMA) [Cryomilling]

IQ MILL_Poly-010

Characteristics: Polymethacrylic acid ester resin (acrylic resin) has high transparency and impact resistance and is easy to form and color thermoplastics.

Application: As a substitute for inorganic glass, it is used for windows of buildings and vehicles, lighting fixture covers, lantern signs, road signs, daily necessities, office supplies, crafts, watch crystals, etc.



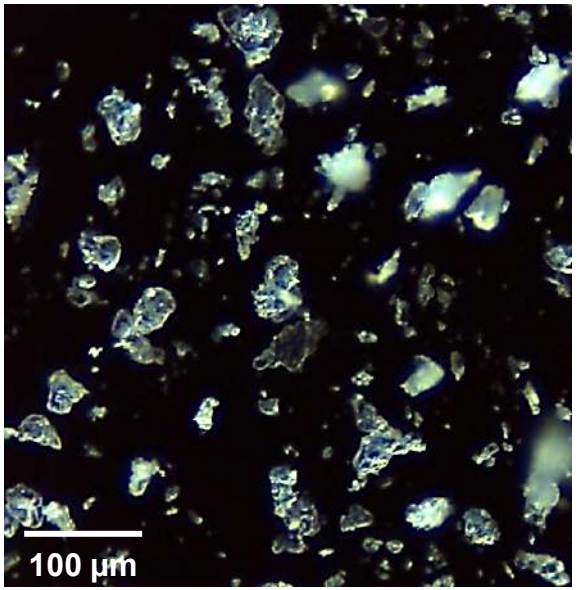
PMMA 0.58 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.58	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	2	1

Ground to a particle size of approx. 10-50 µm (<60 mesh, yield: 95 %)

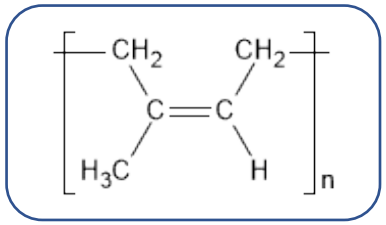


*60 mesh= 0.25 mm opening

Natural rubber (NR) [Cryomilling]

Characteristics: A rubber refined from the sap of a rubber tree, it has excellent mechanical characteristics such as tensile strength, tear strength, and wear resistance, but is inferior in heat resistance, oil resistance, weather resistance, and ozone resistance.

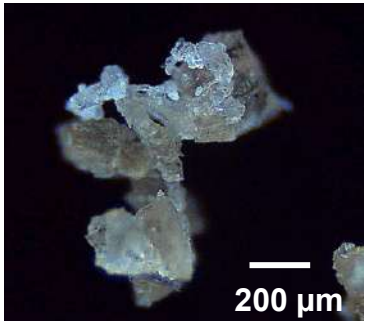
Application: Tires, rubber belts, hoses, footwear, etc. .



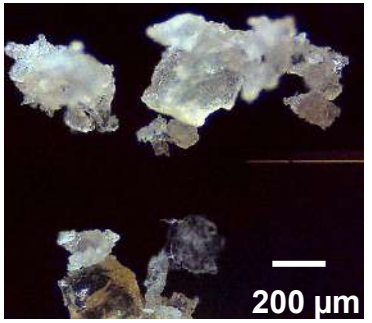
Rubber band 0.53 g

Cryogenic grinding

2500 rpm
x 10 sec
x 1



2500 rpm
x 20 sec
x 2



No significant difference was observed after two repetitions of Cryogenic grinding.

Sample amount (g)	Room temp./Cryogenic	Sample container	Grinding ball	Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	No. of repetitions*
0.53	Cryogenic	Sample container L-Ti	WC-12Φ	2500	10-20	20	1	1-2

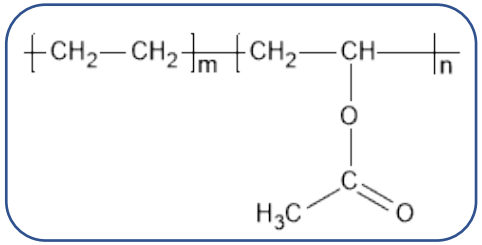
* Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

Ethylene-vinyl acetate copolymer (EVA) [Cryomilling]

IQ MILL_Poly-012

Characteristics: It has excellent low temperature properties, tear strength, impact strength, etc., is highly transparent, and has good appearance and luster. Moreover, it has a low specific density of 30 % or more compared to rubber and PVC, has excellent weather resistance, no ozone aging phenomenon, does not require a plasticizer, and is flexible and non-toxic.

Application: Used as a substitute for inorganic glass, it is used for building and vehicle windows, light fixture covers, lantern signs, road signs, daily necessities, office supplies, crafts, and watch windshields.



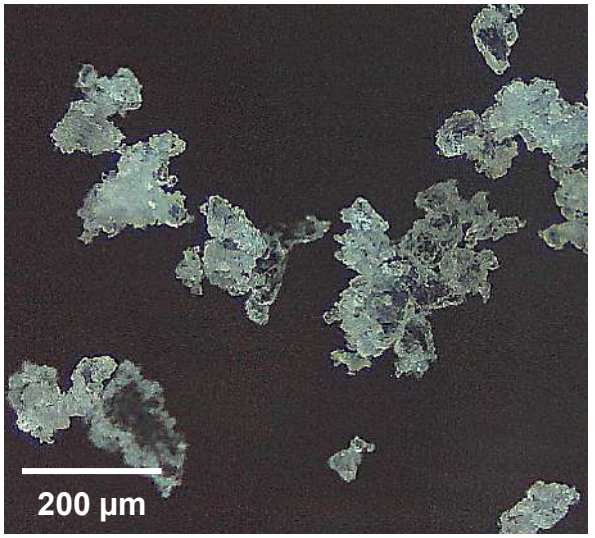
EVA 0.58 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.58	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

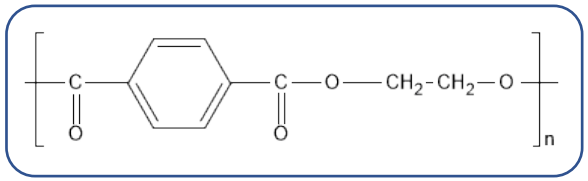
Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	20	20	2	1

(<40 mesh, yield: 100 %)



*40 mesh= 0.42 mm opening

Polyethylene terephthalate (PET) [Cryomilling]

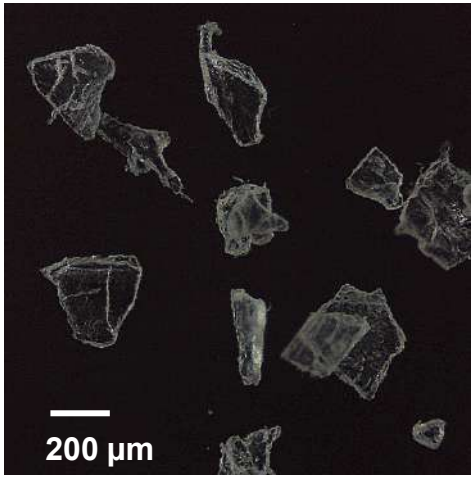


Sample: Three types of PET (cut pieces, 25 µm film, 250 µm film)

PET (cut pieces)

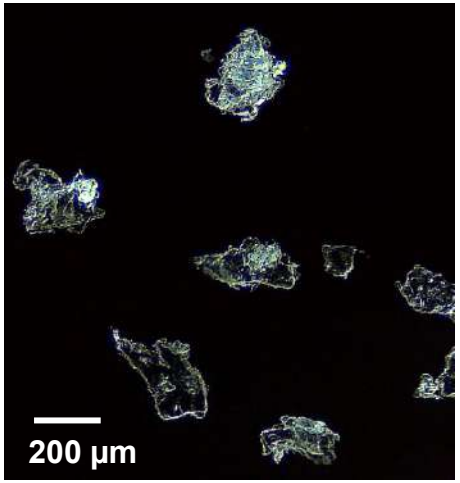
Approx. 0.6 g ground

(<40 mesh, yield: 100 %)



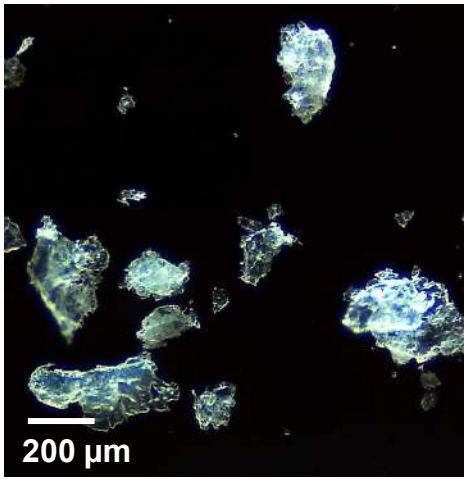
PET (25 µm film)

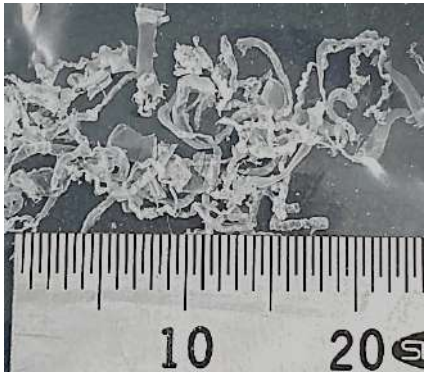
Ground after cutting to
5x5 mm pieces
(<40 mesh, yield: 100 %)



PET (250 µm film)

Ground after cutting to
5x5 mm pieces
(<40 mesh, yield: 100 %)





PET (Cut pieces) 0.58 g

*40 mesh= 0.42 mm opening

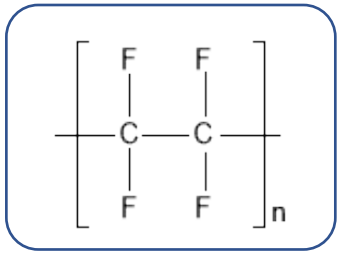
All three samples have similar particle shapes.

Sample amount (g)	Room temp./Cryogenic	Sample container	Grinding ball	Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	No. of repetitions
0.5 – 0.6	Cryogenic	Sample container L-Ti (PC insert tube)	WC-10Φ	3000	30	10	4	1

Polytetrafluoroethylene (PTFE) [Cryomilling]

Characteristics: Polytetrafluoroethylene (PTFE) has excellent heat and chemical resistance and is insoluble in hydrofluoric acid, which is highly corrosive. It has the lowest coefficient of friction of any material discovered to date.

Application: Coated mainly on the surface of cooking utensils, especially metal cooking utensils such as frying pans and pots. Widely used as processing materials in electrical equipment and chemical-mechanical applications that handle high-temperature corrosive fluids.



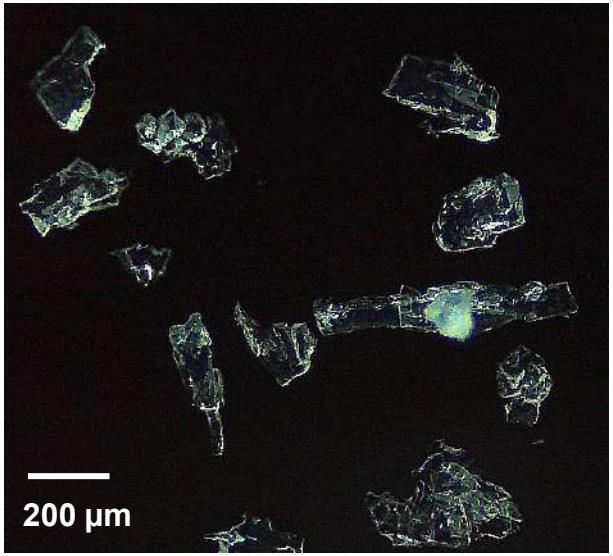
PTFE 0.58 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.58	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
3000	20	10	1	1

(<40 mesh, yield: 100 %)

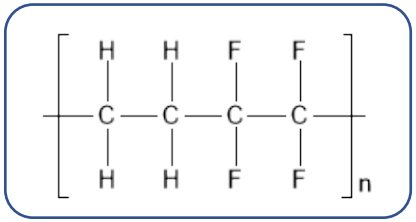


*40 mesh= 0.42 mm opening

Ethylene tetrafluoroethylene copolymer (ETFE) [Cryomilling]

Characteristics: Polytetrafluoroethylene (PTFE) has excellent heat and chemical resistance and is insoluble in hydrofluoric acid, which is highly corrosive. It has the lowest coefficient of friction of any material discovered to date.

Application: Coated mainly on the surface of cooking utensils, especially metal cooking utensils such as frying pans and pots. Widely used as processing materials in electrical equipment and chemical-mechanical applications that handle high-temperature corrosive fluids.



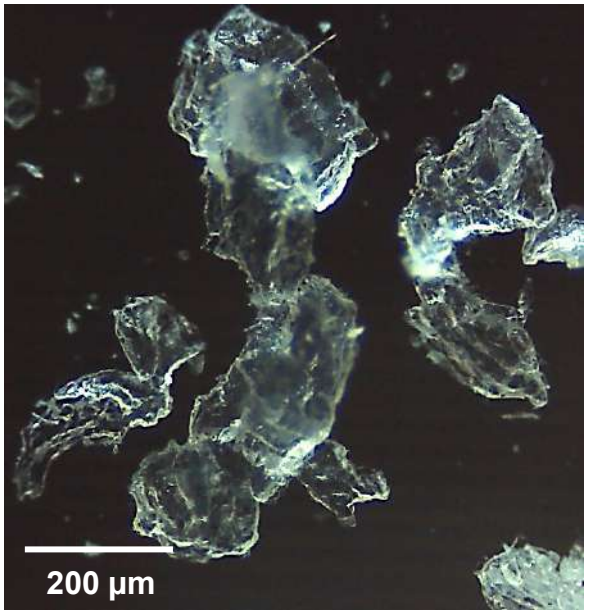
ETFE 0.58 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.58	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions[2)]
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
2500	30	20	2	3

Ground to a particle size of approx. 200 µm (<40 mesh[1)], yield: 42 %)



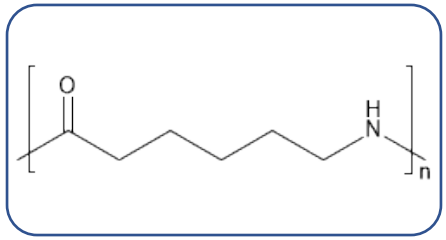
1) 40 mesh= 0.42 mm opening

2) Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

Nylon 6 [Cryomilling]

Characteristics: Nylon 6 fiber is tough and has high tensile strength, elasticity and luster. It is wrinkle and wear resistant and is resistant to chemicals such as acids and alkalis. It absorbs up to 2.4 % moisture but reduces tensile strength. Nylon 6 is generally white but can be dyed in a solution bath prior to fabrication.

Application: Textiles for clothing, bearings, liners, rollers, gears, insulating parts, food processing machine parts, packaging machine parts, etc.



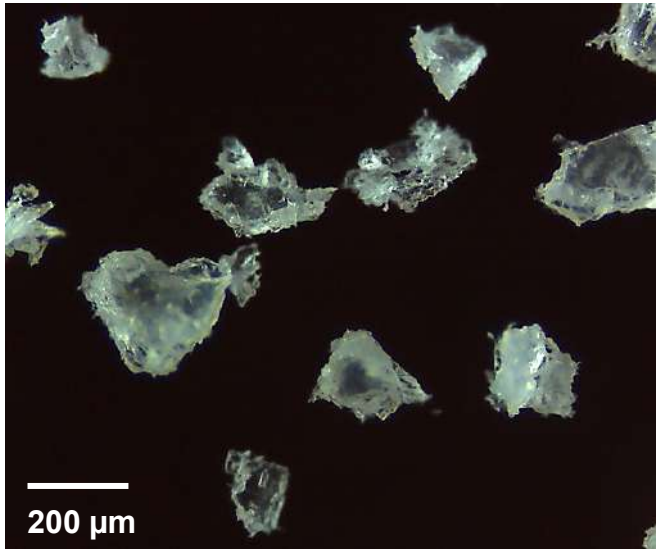
Nylon 6 0.56 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.56	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	20	20	2	1

Ground to a particle size of approx. 100 - 200 µm (<40 mesh, yield: 94 %)

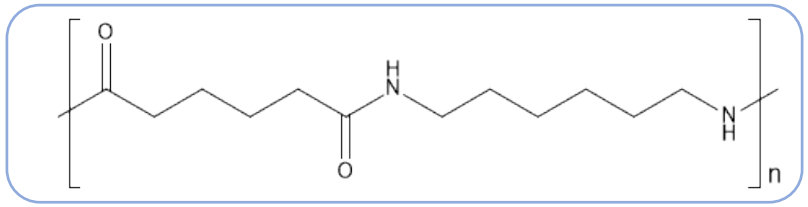


*40 mesh= 0.42 mm opening

Nylon 6,6 [Cryomilling]

Characteristics: Nylon 6,6 is a polyamide with higher heat resistance and mechanical strength than nylon 6, with a melting point around 265 ºC and specific gravity of 1.14. It is one of the strongest materials among engineering plastics. In addition to heat resistance, it has excellent oil resistance, wear resistance, and lubricating properties.

Application: Textiles for clothing, airbags, bearings, liners, rollers, gears, insulating parts, etc.



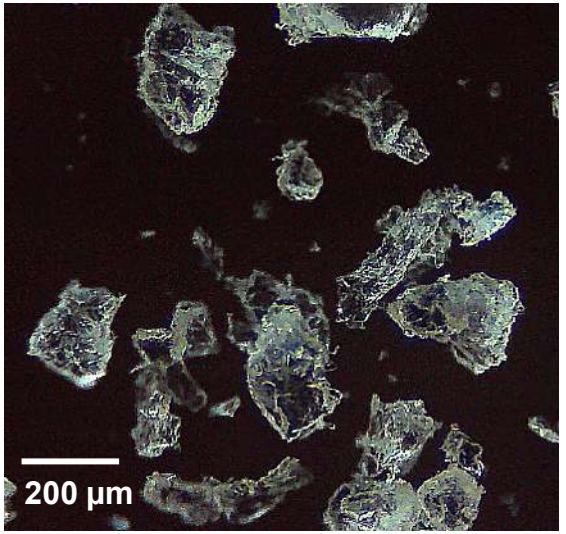
Nylon 6,6 0.58 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.58	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	2	1

(<40 mesh, yield: 100 %)

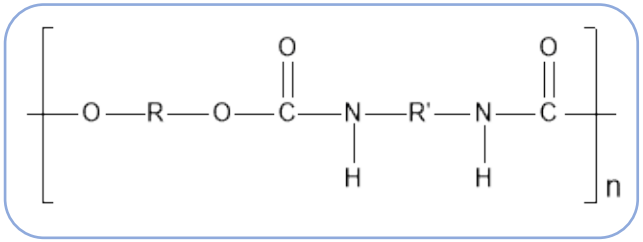


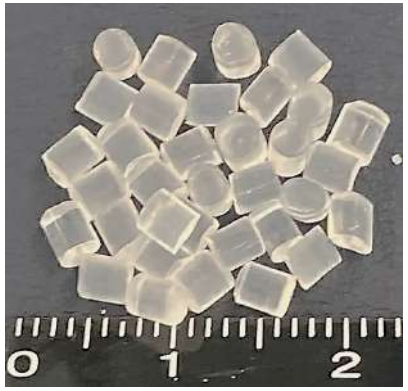
*40 mesh= 0.42 mm opening

Polyurethane (PU) [Cryomilling]

Characteristics: Excellent in wear resistance, impact resistance, oil resistance, and low-temperature properties. However, it does not have excellent heat resistance and is prone to degradation under high temperature and humidity.

Application: Paints, adhesives, sponges, sealants and caulking materials, fillers, heat insulators, soundproofing materials, textile products, footwear products, various automotive parts, etc.





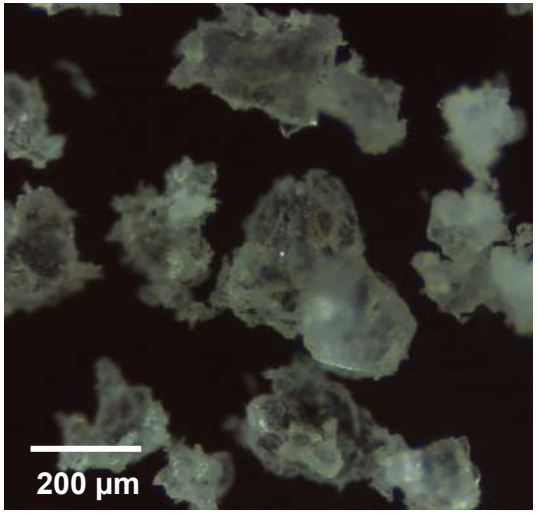
PU 0.55 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.55	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
3000	20	20	2	1

(<40 mesh, yield: 97 %)

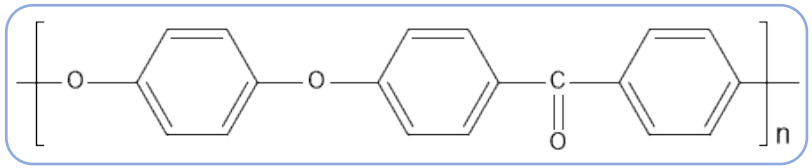


*40 mesh= 0.42 mm opening

Polyetheretherketone (PEEK) [Cryomilling / Room temp.]

IQ MILL_Poly-019

Characteristics: This thermoplastic resin has very high thermal resistance (glass transition temperature of 143 ºC and melting point of 343 ºC). It also has excellent flame resistance, mechanical properties, fatigue resistance, abrasion resistance, dimensional stability, and processability, and can be processed by ordinary injection molding machines, or made into film or nonwoven fabric.



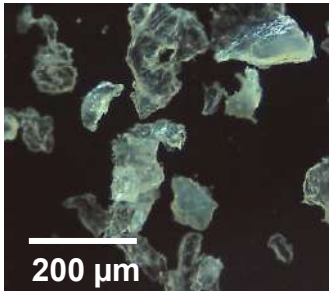
Sample: PEEK pellets (no pretreatment)

Pellets (0.52 g)	3000 rpm x 30 sec (Room temp.[1])	3000 rpm x 30 sec (Cryogenic grinding[2])

1. In room-temperature grinding, the whole sample turns blackish and can only be ground marginally.
2. At one cryogenic grinding, the pellets were deformed into small flakes.

Pellets (0.52 g)

3000 rpm x 30 sec (Cryogenic grinding 4 times)



1) 40 mesh= 0.42 mm opening

- Cryogenic grinding was repeated four times to obtain finely ground particles of 40 mesh[1)] or less. Yield: 83 %.
- In addition, with 1 g of sample, less than 40 mesh was obtained by two additional repetitions of cryogenic grinding. Yield: 58 %.

Sample amount (g)	Room temp./Cryogenic	Sample container	Grinding ball	Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	No. of repetitions[2)]
0.52	Room temp. / Cryogenic	Sample container L-Ti	WC-12Φ	3000	30	20	1	1-4

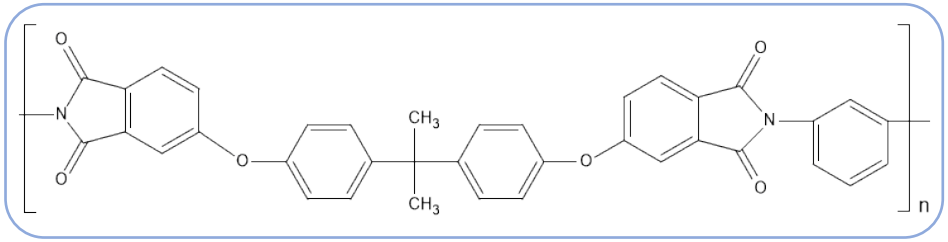
2) Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

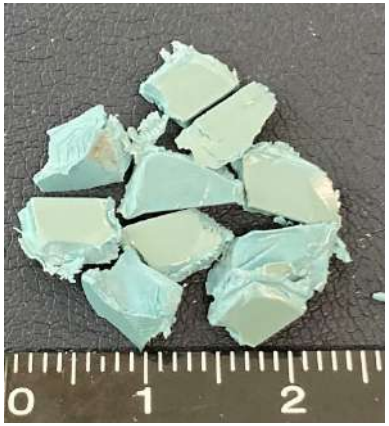
Polyetherimide (PEI) [Room temp.]

IQ MILL_Poly-020

Characteristics: One of the super engineering polymers, it is flame retardant with excellent chemical resistance, water resistance, and thermal resistance. Even if it were to burn, it would generate little smoke. It also has excellent electrical properties, weather resistance, and dielectric breakdown strength. It is used in aircraft parts.

➢ **Pretreatment:**
A portion of sample was cut into approx. 5 mm pieces using nippers.





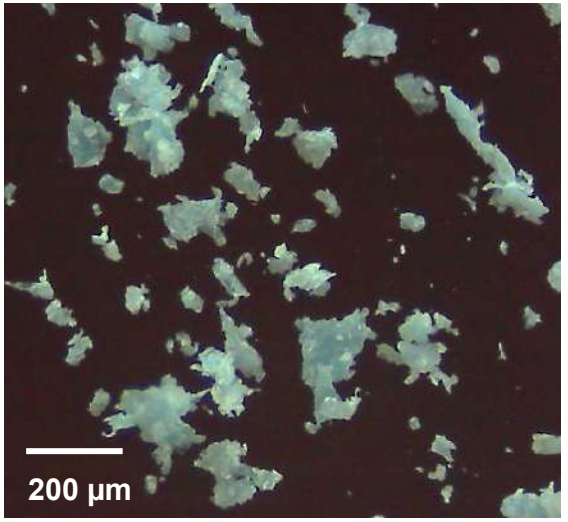
PEI 0.53 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.53	Room temp.	Sample container L-Ti	WC-12Φ

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
3000	20	20	10	1

(<40 mesh, yield: 92 %)



*40 mesh= 0.42 mm opening

Copy paper [Cryomilling]

➢ **Pretreatment:**
Copy paper is cut with a knife to about 10 mm in size as shown below.

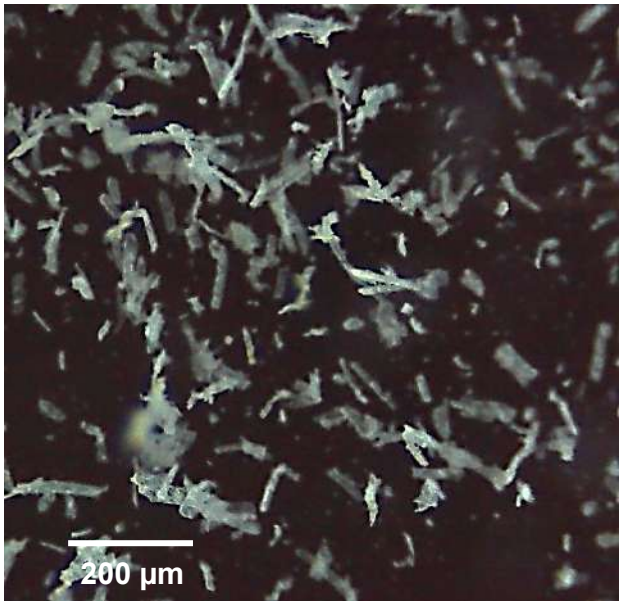
Copy paper 0.23 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.23	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	20	-	1	-

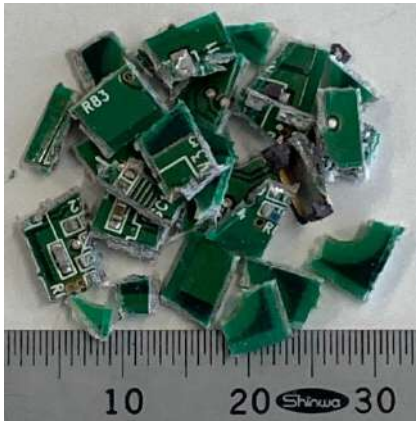
(<40 mesh, yield: 90 %)



*40 mesh= 0.42 mm opening

Electronic circuit boards [Room temp.]

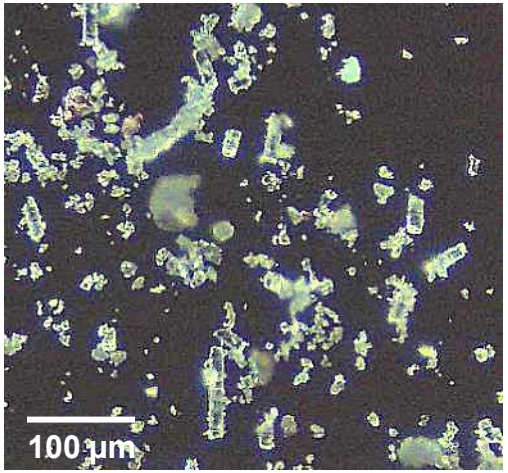
➢ **Pretreatment:**
Portions of a circuit board are cut into approx. 10 mm pieces using nippers.



Electronic circuit boards (2.1 g)

Room temp. grinding

(<40 mesh, yield: 100 %)



*40 mesh= 0.42 mm opening

Grinding ball WC-10Φ was selected:
When WC-12Φ was used, the grinding ball was stuck between pieces of the circuit board, making them ungrindable.

Sample amount (g)	Room temp./Cryogenic	Sample container	Grinding ball	Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	No. of repetitions
2.1	Room temp.	Sample container L-Ti	WC-10Φ	2500	30	20	10	-

Foamed polystyrene (PS) [Cryomilling]

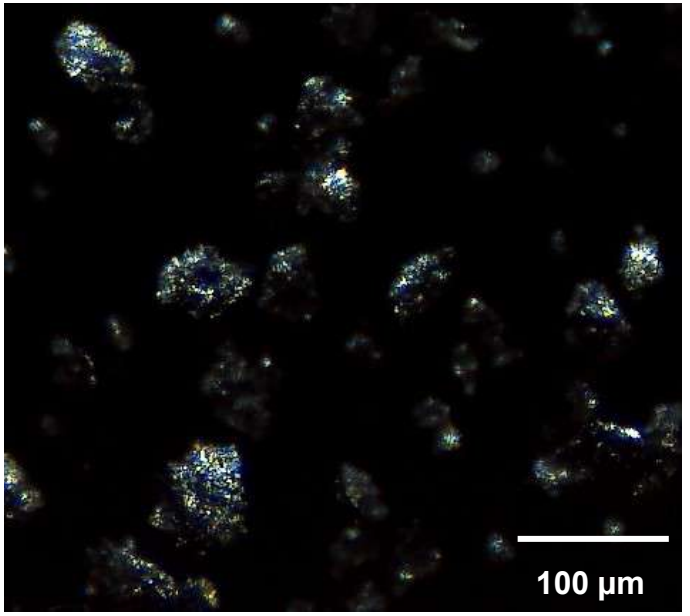
Sample courtesy of Institute for Plastics and Recycling Technology (Leibniz Universität Hannover)

Sample amount (g)	Room temp./ Cryogenic	Sample container	Grinding ball
0.06	Cryogenic	Sample container L-Ti	WC-6Φ x 5

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
3000	30	-	1	1

(<40 mesh, yield:99%)



*40 mesh＝0.42 mm opening

Polyethylene (PE) form [Cryomilling]

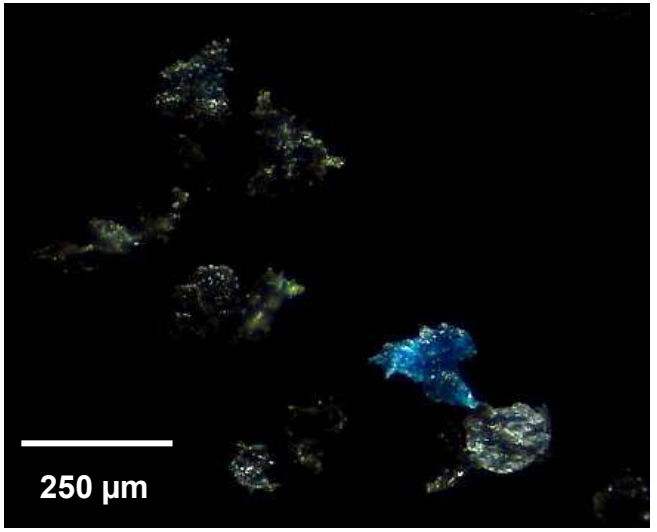
Sample amount (g)	Room temp./ Cryogenic	Sample container	Grinding ball
0.17	Cryogenic	Sample container L-Ti	WC-6Φ x 5

Cryogenic grinding

Grinding conditions				No. of repetitions*2
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	2	3

*1

(<40 mesh, yield: 77%)



*40 mesh＝0.42 mm opening

Sample courtesy of Institute for Plastics and Recycling Technology (Leibniz Universität Hannover)

*1: Ethanol was added to the grinding container to prevent aggregation due to static electricity before recovery.

*2: Immersion in liquid nitrogen followed by grinding is considered one repetition. The initial immersion time in liquid nitrogen is 10 minutes, while subsequent immersion times are 5 minutes.

Low density polyethylene (LLDPE) film [Cryomilling]

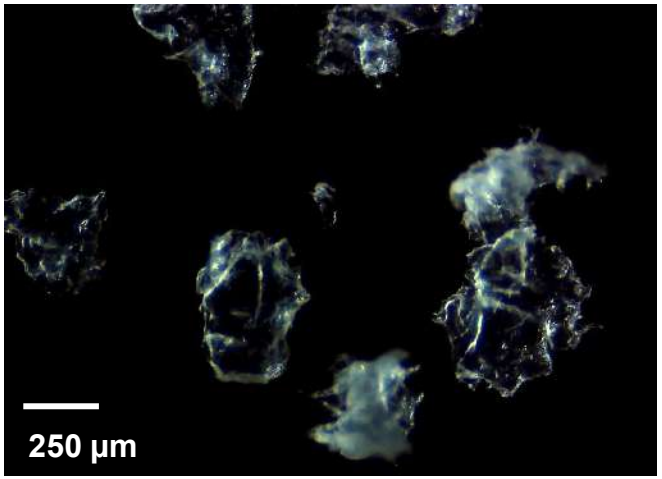
IQ MILL_Poly-025

Sample amount (g)	Room temp./ Cryogenic	Sample container	Grinding ball
0.3	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	2	1

(<40 mesh, yield: 47%)



*40 mesh＝0.42 mm opening

Sample courtesy of Institute for Plastics and Recycling Technology (Leibniz Universität Hannover)

Polyamide fiber [Room temp.]

Sample amount (g)	Room temp./ Cryogenic	Sample container	Grinding ball
0.4	Room temp.	Sample container L-Ti	WC-6 x 5

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	60	3	1

*1

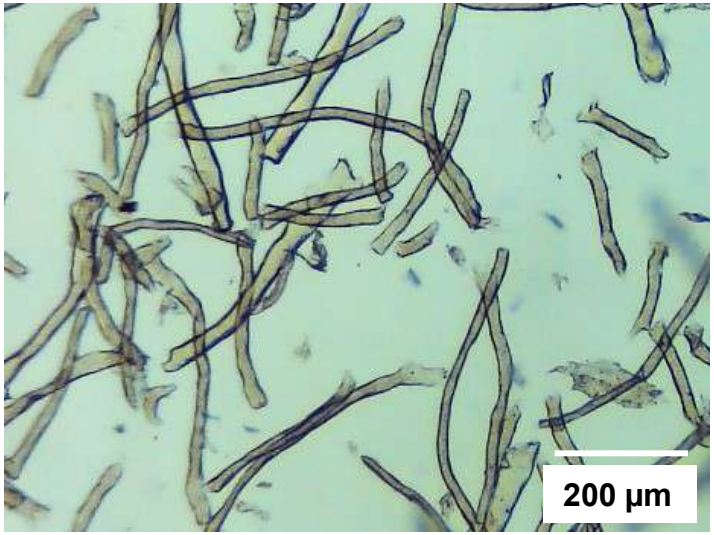
Sample courtesy of Institute for Plastics and Recycling Technology (Leibniz Universität Hannover)

***1: Fiber aggregates**

Ethanol added

Dispersion

(<40 mesh, yield:84%)



*40 mesh＝0.42 mm opening

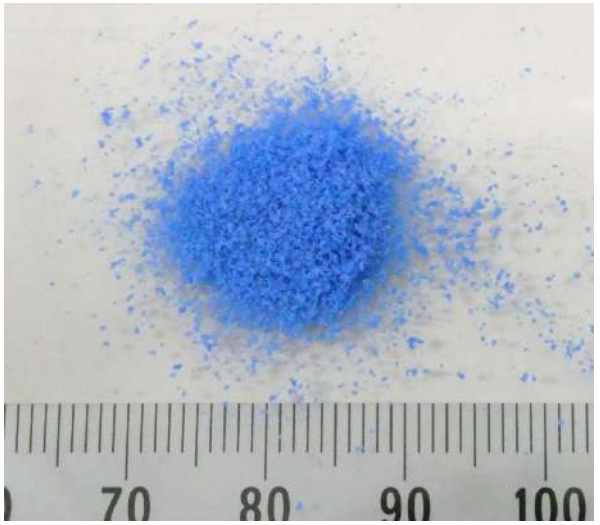
Nitril glove【Cryomilling】

➢**Pretreatment**：Nitril glove is cut with scissors to the appropriate size.

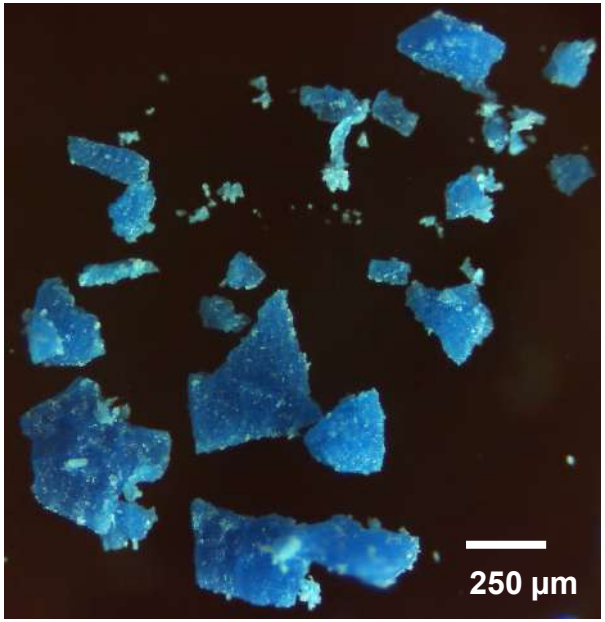
Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.42	Cryogenic	L-SS	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	10	10	2	1



(<40 mesh, yield: 99 %)



*40 mesh= 0.42 mm opening

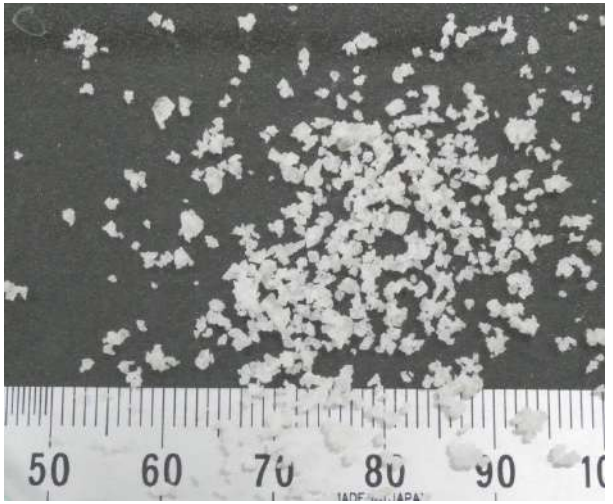
Styrene-butadiene rubber (SBR)【Cryomilling】

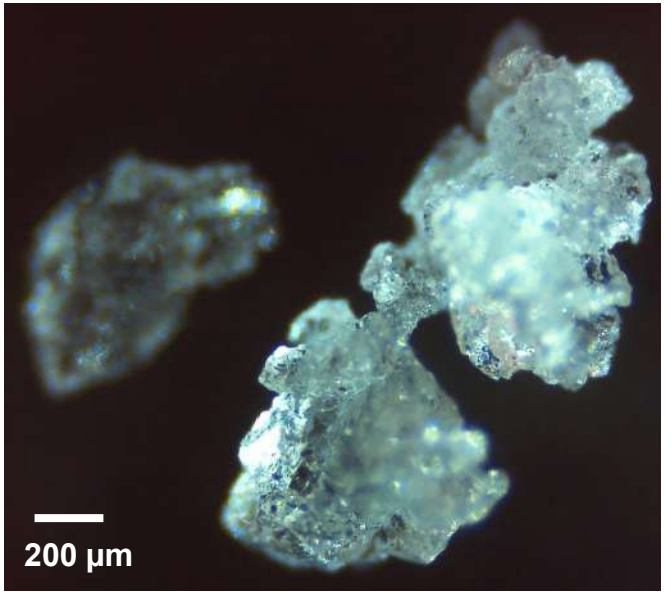
➢**Pretreatment**：SBR is cut into 3-5 mm pieces with nippers.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.46	Cryogenic	L-SS	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	10	10	2	1





Cardboard【Cryomilling】

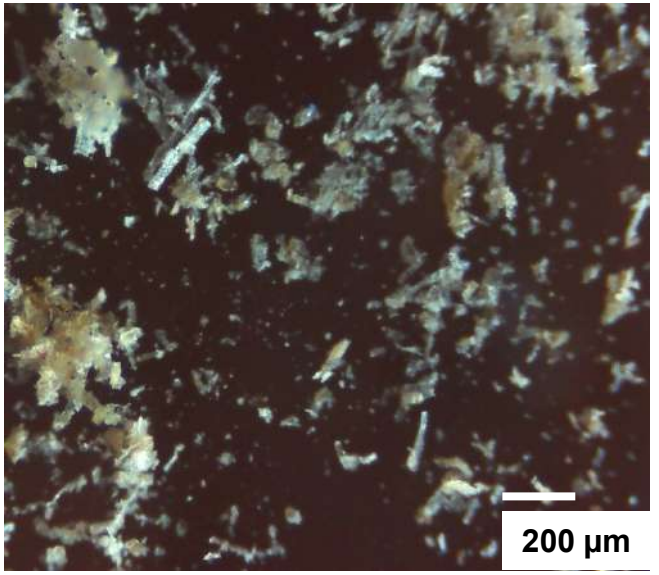
➢**Pretreatment**：Cardboard is cut with scissors to the appropriate size.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.19	Cryogenic	L-SS	Zr-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	10	10	2	1

(<40 mesh, yield: 93 %)



*40 mesh= 0.42 mm opening

Boar canines [Room temp.]

Characteristics: Wild boar teeth are enamel, hard as crystal, and very difficult to crush. These were used to study the effects of strontium in the 2011 Fukushima nuclear accident.

➢**Pretreatment:**
Canine teeth are cut into 3-5 mm pieces with nippers.

Canine tooth

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
1 canine tooth	Room temp.	Sample container L-Ti	Zr-6Φ x 1

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
1500	60	10	3	-

Sample courtesy of prof. H. Ishiniwa
(Fukushima University)

Tooth of fox, raccoon and raccoon dog [Room temp.]

IQ MILL_Bio-001-2

Characteristics: The teeth of these animals are enamel, as hard as quartz, making them very hard, and extremely difficult to grind. They were used in a study of the 2011 Fukushima nuclear accident impact to investigate the impact of the strontium.

➢**Pretreatment:** A tooth is cut into 3-5 mm pieces with nippers.

Fox raccoon raccoon dog

Sample courtesy of prof. Y. Takagai (Fukushima University)

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
1 canine tooth	Room temp.	Sample container L-Ti	Zr-12Φ x 1

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
2000	20	10	2	-

After grinding of fox teeth
(Other teeth are similarly ground.)

5 cm

Shellfish [Room temp.]

Clam Turban shell

Room temp. grinding

➢ **Pretreatment**
Samples are cut into about 10 mm pieces using nippers.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
2.0	Room temp.	Sample container L-Ti	Zr-12Φ

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
2500	20	20	4	1

Bark of young shoot of moso bamboo [Room temp. wet]

This is difficult to grind. Used for DNA research.

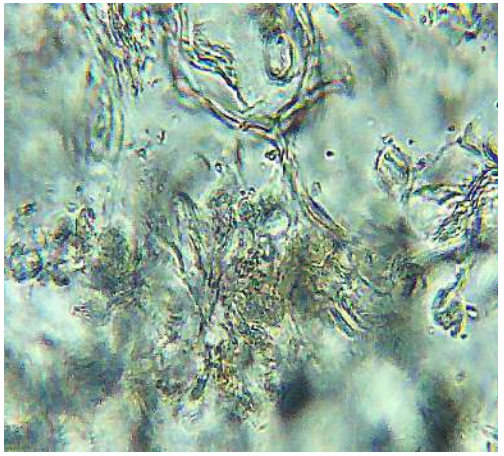
Sample courtesy of prof. S. Kaneko
(Fukushima University)

Disposal PP Container (2 mL):
DNeasy® Plant Mini Kit Buffer solution 0.3 mL

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.53	Room temp./wet	Disposable PP Container (2 mL)	Zr-5Φ x 1 Zr-3Φ x 1

Room temp. wet grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
2000	10	10	2	-

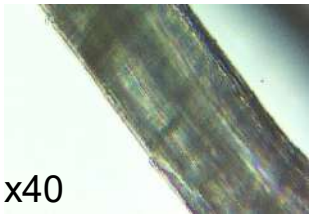


x40

50 µm

Hemp cord [Room temp. wet]

➢**Pretreatment**: Hemp twines are cut into 3-5 mm pieces with scissors.



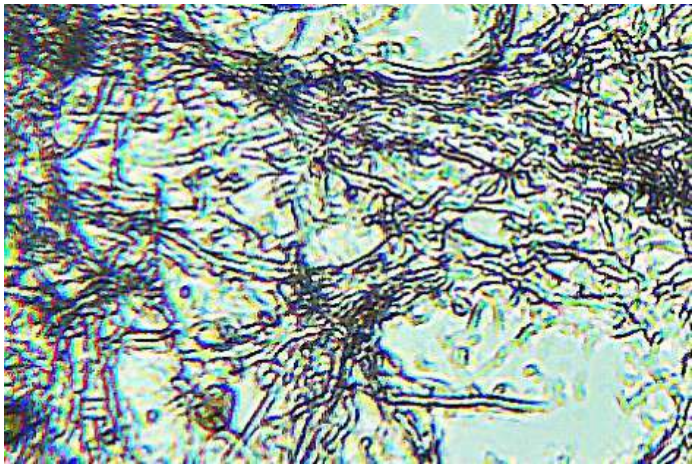
Approx.10 mm; 7.7 mg
(Before cutting)

Container: Disposable PP Container (2 mL):Distilled water 1.0 mL

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.53	Room temp. wet	Disposable PP container	Zr-6Φ x 2

Room temp. wet grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
1500	60	10	10	-



50 µm x40

Wood chips [Room temp.]

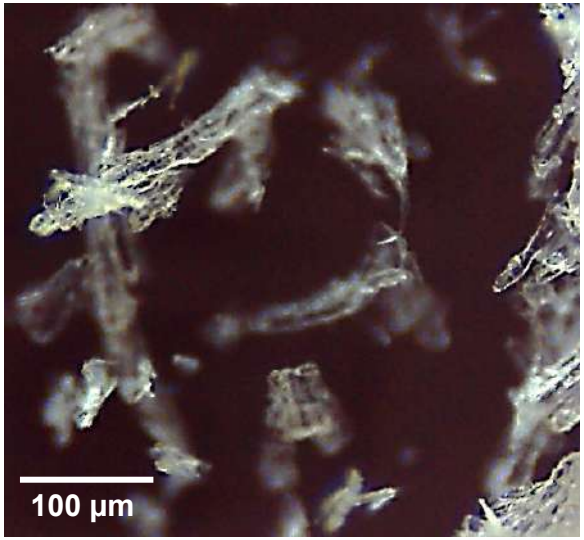
➢ **Pretreatment:** Toothpicks are cut into 5 mm pieces with nippers.

Wood chips 0.32 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.32	Room temp.	Sample container L-Ti	Zr-12Φ

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	20	3	-



Cotton [Room temp.]

➢**Pretreatment**：A piece of cotton is cut into 3-5 mm pieces with scissors.

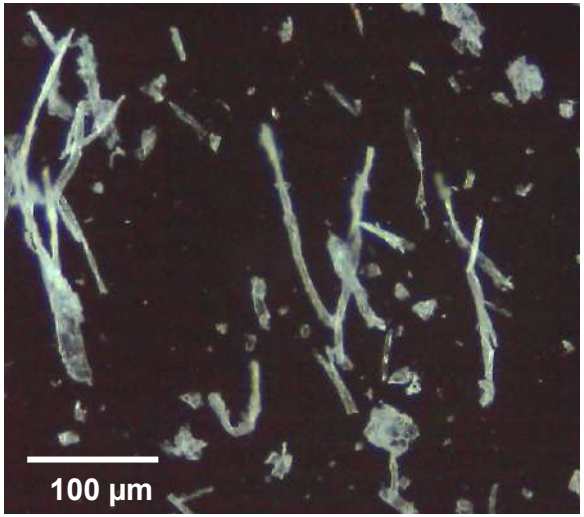
Cotton 0.21 g

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.21	Room temp.	Sample container L-Ti	WC-12Φ

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	20	20	10	-

(<40 mesh, yield: 92 %)



*40 mesh= 0.42 mm opening

Dried squid [Cryomilling]

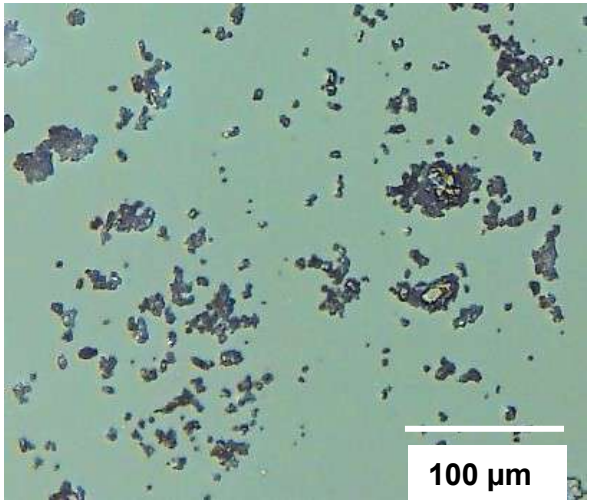
➢**Pretreatment**:
Dried squid is cut into 3-5 mm pieces with nippers.

* A thin PC insert tube is installed in the container.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.61	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	-	1	-



Beef jerky [Cryomilling]

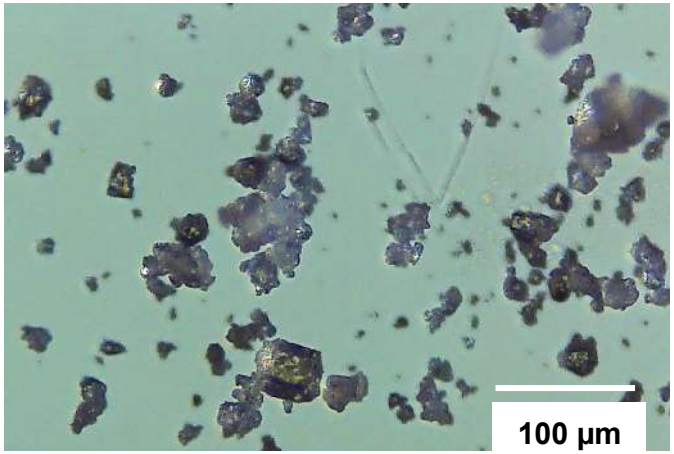
➢**Pretreatment**:
Beef jerky is cut into 3-5 mm pieces with nippers.

* A thin PC insert tube is installed in the container.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
1.4	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	-	1	-



Shell string [Cryomilling]

➢**Pretreatment**: A shell string is cut into 3-5 mm pieces with nippers.

* A thin PC insert tube is installed in the container.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.84	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	-	1	-

Clay-like solids

Vacuum Dry

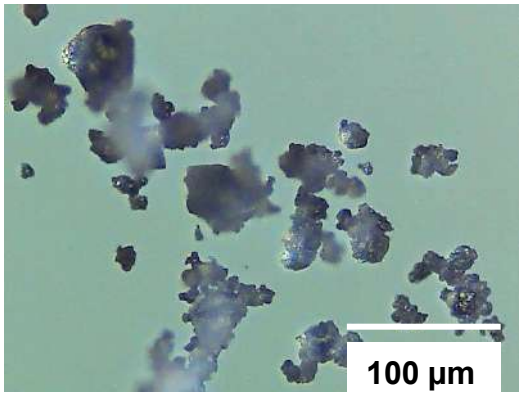
Temp.	Drying time
(°C)	(hour)
40	24

Powder lumps

Room temp. grinding

Milling speed	Grinding time	Pause time	No. of cycles
(rpm)	(sec)	(sec)	(Cycle)
1500	10	-	1

After room temp. grinding



Sea squirts [Cryomilling]

➢**Pretreatment**: A piece of sea squirt is cut into about 3-5 mm pieces with nippers.

* A thin PC insert tube is installed in the container.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
0.76	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	-	1	-

Clay-like solids

Vacuum Dry

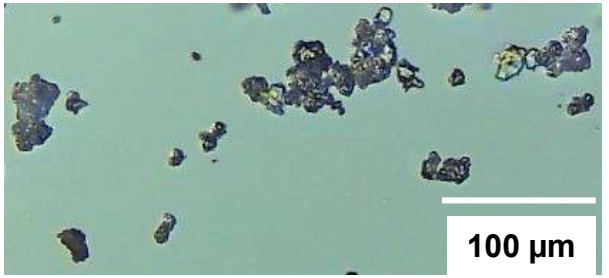
Temp.	Drying time
(ºC)	(hour)
40	24

Powder lumps

Room temp. grinding

Milling speed	Grinding time	Pause time	No. of cycles
(rpm)	(sec)	(sec)	(Cycle)
1500	10	-	1

After room temp. grinding



Seaweed stem [Cryomilling]

➢**Pretreatment**: Wakame stem is cut into 3-5 mm pieces with nippers.

* A thin PC insert tube is installed in the container.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
1.1	Cryogenic	Sample container L-Ti	WC-12Φ

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	30	-	1	-

Paste-like solids

Vacuum Dry

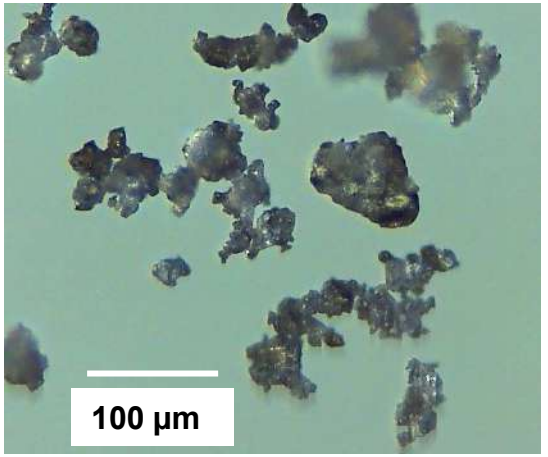
Temp.	Drying time
(ºC)	(hour)
40	24

Solid (hard)

Room temp. grinding

Milling speed	Grinding time	Pause time	No. of cycles
(rpm)	(sec)	(sec)	(Cycle)
2500	10	-	1

After room temp. grinding



Almond seed (shell) [Room temp.]

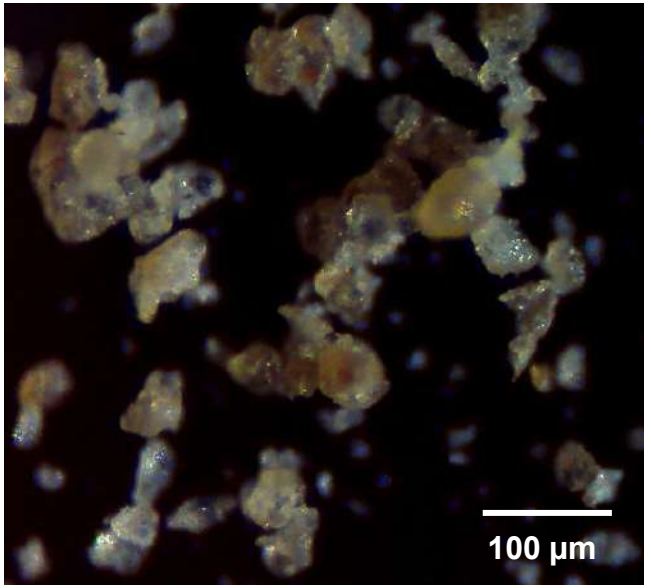
➢**Pretreatment:** Almond shells are crushed in a vise.

Sample amount (g)	Room temp./ Cryogenic	Sample container	Grinding ball
0.93	Room temp.	Sample container L-Ti	Zr-12Φ

Room temp. grinding

Grinding conditions				No. of repetition
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(cycle)	
3000	30	-	1	1

(< 40 mesh, yield：76%)



*40 mesh＝0.42 mm opening

Almond seed (edible part) [Room temp.]

➢**Pretreatment:** Skin is peeled off with a knife.

*A thin PC insert tube installed inside the container

Sample amount (g)	Room temp./ Cryogenic	Sample container	Grinding ball
0.57	Room temp.	Sample container L-Ti	WC-12Φ

Room temp. grinding

Grinding conditions				No. of repetition
Milling speed (rpm)	Grinding time (sec)	Pause time (sec)	No. of cycles (Cycle)	
2500	20	-	1	1

Paste-like solids

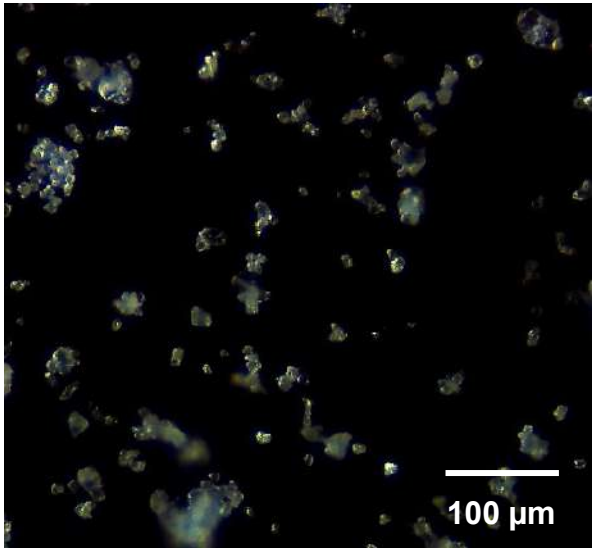
Organic solvent added

Fat is removed

Solvent is removed by centrifugation

2000 rpm, 3 min

Allowed to dry for 1-2 days



Candy [Room temp.]

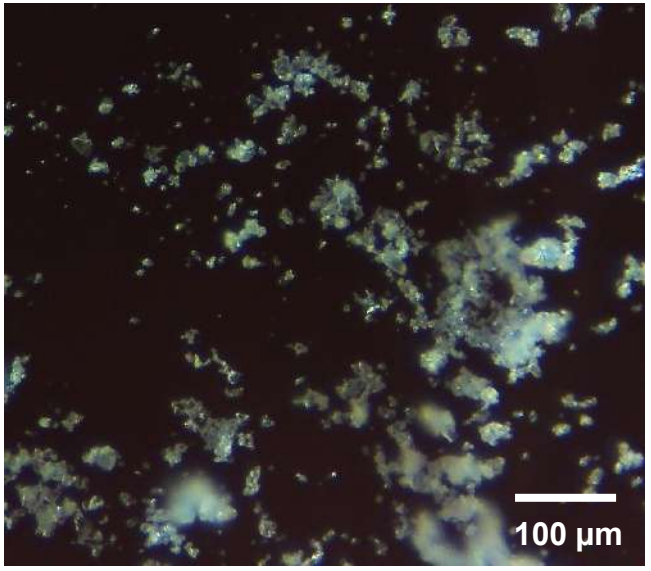
➢**Pretreatment**: A candy is cut in half with nippers.

Sample amount (g)	Room temp. /Cryogenic	Sample container	Grinding ball
1.34	Room temp.	L-SS	Zr-12Φ

Room temp. grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
3000	10	-	1	1

(<40 mesh, yield: 99 %)



*40 mesh= 0.42 mm opening

[Minute amount]Leaves of houseplants [Cryomilling]

➢**Pretreatment**: A leaf is cut with scissors to the appropriate size.

Sample amount (mg)	Room temp. /Cryogenic	Sample container	Grinding ball
18	Cryogenic	S-SS	Zr-5Φ×1 pcs.

Cryogenic grinding

Grinding conditions				No. of repetitions
Milling speed	Grinding time	Pause time	No. of cycles	
(rpm)	(sec)	(sec)	(Cycle)	
2000	10	10	2	1

Paste-like solids

Allowed to dry at room temp.

or

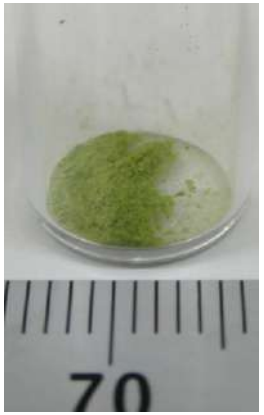
Vacuum Dry

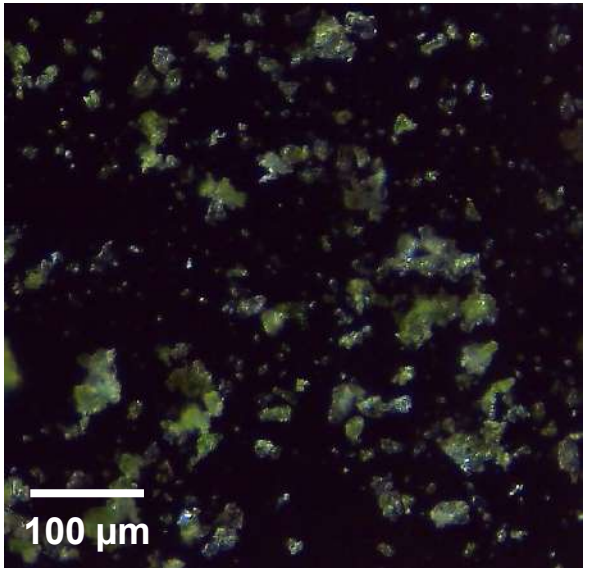
Temp.	Drying time
(°C)	(hour)
40	2

Room temp. grinding

Milling speed	Grinding time	Pause time	No. of cycles
(rpm)	(sec)	(sec)	(Cycle)
1500	10	-	1

After room temp. grinding





Glossary

Term	Description
PC insert tube	Polycarbonate tube that is inserted to sample container.
Disposable PP container	Disposable polypropylene container
Sample container L-Ti	Sample container, large, made of titanium
Sample container L-SS	Sample container, large, made of hardened stainless steel
WC-12Φ grinding ball	Tungsten carbide (WC) grinding ball, 12 mm diameter
Zr-12Φ grinding ball	Zirconia or zirconium dioxide (ZrO_2) grinding ball, 12 mm diameter
Milling speed	Grinding speed or rotation speed of motor
Grinding time	Time during which sample is ground
Pause time	Time between runs or time during which grinding is stopped
No. cycles	No. of grinding sequences including grinding time and pause.
No. of repetitions	No. of whole programmed grinding cycles that can include liquid nitrogen cooling, grinding, and pause time when cryomilling.