TECHNOLOGIES TO WATCH IN 2024 (1)

SCALE-UP OF MICROWAVE REACTORS

— CONTRIBUTION TO GHG EMISSION REDUCTIONS ACROSS DIVERSE SECTORS FROM CHEMICAL SYNTHESIS TO METAL SMELTING —

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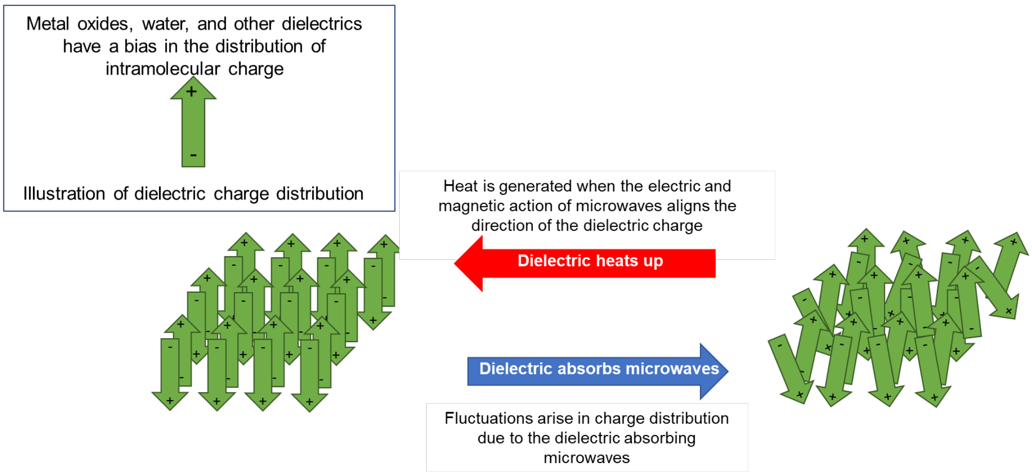
ABOUT MICROWAVE REACTORS

A microwave reactor is a device that converts electricity into microwaves and irradiates them to heat an object or cause a chemical reaction. This section first describes microwaves and then discusses their advantages and why microwave reactors can contribute to decarbonization.

(1) MICROWAVES

Microwaves are electromagnetic waves with wavelengths from 1 mm to 1 m and frequencies from 0.3 GHz to 300 GHz. A familiar example of their application is the microwave oven. Microwaves of frequency 2.45 GHz can directly vibrate water molecules in liquids, and microwave ovens use this property to heat things that contain water. While ordinary heaters heat indirectly using air or liquid, microwaves directly vibrate materials that have charge bias in their molecules (dielectrics), which in principle results in higher heating efficiency (Figure 1). For this reason, applications have been developed in the form of environmentally friendly heating methods or chemical reaction processes.

Figure 1: Structural change and heat generation in a dielectric due to microwave irradiation



Source: Prepared by Mitsui & Co. Global Strategic Studies Institute with reference to "Changing Chemistry: Microwaves and Thermal Catalysts," (Shozo Yanagida and Takeko Matsumura)

Hyperthermia is a heat treatment in which cancer and other malignant tumors are irradiated to kill them[1]. Similar to the effect of this therapy, microwaves are thought to interact with cells. However, this paper does not discuss the effects on the human body because the irradiation target is limited to raw materials for industrial products

[1] "Changing Chemistry: Microwaves and Thermal Catalysts" (*kagaku wo kaeru maikuroha netsu shokubai*) [in Japanese], Shozo Yanagida and Takeko Matsumura (Kagakudoujin, 2004)

and usage is assumed to be under conditions where there is no risk of microwave leakage to the surrounding environment or irradiation of the human body.

(2) THE HIGH GHG EMISSION REDUCTION EFFECT OF MICROWAVE REACTORS

Research into industrial applications of microwave reactors has been conducted since around the year 2000. For a long time, there have been only a small number of application examples such as cosmetic ingredients, due to issues such as the high cost of equipment and the difficulty of scaling up. However, 20-years of R&D results have been accumulated, in addition to which it has recently been said that energy efficiency must be doubled in order to achieve the 2030 target of 1.5°C or lower global warming. Accordingly, the value of microwave reactors, which are energy efficient in principle, is being re-evaluated.

PROMISING FIELDS OF APPLICATION

Figure 2 summarizes studies into the application of microwave reactors divided into three areas — plastic recycling, metal smelting, and metal recycling — which are explained below.

Figure 2: Status of investigations into the application of microwave oscillators

Company/University Name	Country	Material	Development Phase (Equipment Performance)	Overview
Microwave Chemical	Japan	Acrylic resin	Demonstration facility (processing capacity: 50 – 250 L)	Constructing a demonstration facility for monomerization in collaboration with Mitsubishi Chemicals
		Shredder dust (PP) Thermosetting sheet molding compound Soft polyurethane foam	Bench scale (processing capacity: 5 – 50 L)	Investigating monomerization in collaboration with Mitsui Chemical
		Lithium	Pre-bench scale (processing capacity: approx. 100 g)	Developing low-carbon lithium ore refining technology in collaboration with Mitsui & Co. Developing technology for dissolution of spodumene concentrate under development with National Institutes for Quantum Science and Technology
		Nickel	Demonstration (processing capacity: approx. 50 kg/hour)	Produced small demonstration facility for the sintering process with Pacific Metals
Gr3n	Switzerland	Waste PET	Aiming to produce 40,000 tons/year of virgin PET chips	Planning to construct a monomerization plant scheduled for operation in 2027
Pyrowave	Canada	Waste polystyrene	Pilot (processing capacity per unit: 1,000 t/year, 4.8 t/day)	Combining pilot-scale modules to ensure the scale required for commercial production. Offering licensing in addition to equipment sales
Teledyne e2v	UK	Copper	Commercial scale (processing capacity: 3,000 t/hour)	System for Rio Tinto's extraction process
C-Tech Innovation	UK	Steel	Pilot (processing capacity: 1 t/day, frequency: 2.45 GHz, output: 2 kW)	Conducted reduction testing by hybrid kiln using microwaves in a project for the development of direct hydrogen reduction technology
Metso	Finland	Steel	Scale-up under investigation (processing capacity: 1 t/hour)	Developed the BioIron process, which uses agricultural residues as a reductant in replacement of coke, and microwave heating to turn iron oxide into metallic iron Scale-up under investigation
Sepro Mineral Systems	Canada	Copper, nickel, gold ore	Commercial scale (processing capacity: 1,000 t/hour)	Developed equipment to mill along grain boundaries by microwave irradiation in collaboration with University of Alberta. Confirmed effect of increasing separation efficiency of minerals after crushing in addition to energy savings
University of Oulu	Finland	Zinc	Laboratory (frequency: 2.45 GHz, output: 1.1 kW)	Technology for recovery of zinc from blast furnace slag
Ritsumeikan University	Japan	Zinc	Lab (frequency: 2.45 GHz, output: 7.5 kW)	Technology for recovery of zinc from electric arc furnaces
		Lithium-ion batteries Lead batteries		Possible to process recovery of cobalt from cathode materials of lithium-ion batteries and lead from lead batteries in a few to a few tens of seconds Processing being possible in the atmosphere also advantageous for low-cost, small-scale equipment

Plastic recycling, Metal smelting, Metal recycling)

Source: Prepared by Mitsui & Co. Global Strategic Studies Institute from various sources (current as of November 2023)

(1) PLASTIC RECYCLING

Although mechanical recycling[2] is the leading recycling method for plastics, it has the problem that performance degradation due to repeated processing is unavoidable. Technologies to solve this problem include monomerization, in which plastics are decomposed into monomers by heat[3]; conversion into oil, in which plastics are decomposed into an oil-like substance similar to the raw material naphtha; and solvolysis, in which a solvent is added, and heat applied. However, these technologies require a large amount of energy to decompose the plastic, which has resulted in a trade-off. Therefore, there are high expectations for the use of microwave

[2] A method of mechanically shredding and melting waste plastic and reusing it in plastic products
[3] Low molecular weight molecules that form the raw materials for synthesizing polymers, the main raw materials of plastics

reactors to increase processing efficiency.

Microwave Chemical (Japan) is one of the few companies in the world with a proven track record of scaling up microwave reactors. The company is considering monomerization of automotive shredder dust and thermosetting sheet molding compound in collaboration with Mitsui Chemicals, and monomerization of acrylic resin in collaboration with Mitsubishi Chemical. Figure 3 shows a photograph of a demonstration facility for the monomerization of acrylic resin.

Figure 3: Demonstration facility for monomerization of acrylic resin

Source: Facilities section of the Microwave Chemical website
Pilot scale microwave pilot equipment for PMMA decomposition
https://mwcc.jp/plawave/facility/ (last accessed December 27, 2023)

Outside of Japan, Gr3n (Switzerland), a startup that develops chemical recycling technology for resins, is planning to build a polyethylene terephthalate (PET) monomerization plant in Spain. The company expects to source used PET from both factories that process PET and consumers, and will accept polyester fiber as well as drink bottles. Since microwaves can selectively break down PET into monomers, Gr3n says it can also handle polyester fibers blended with up to 30% polyurethane or cotton. In addition, Pyrowave (Canada) has a modular technology platform that can monomerize waste polystyrene. The platform consists of microwave reactors with an annual production capacity of 1,000 tons of styrene monomer per unit, enabling a reduction of greenhouse gas emissions by a factor of five to seven compared to production of virgin styrene monomer. Pyrowave has also realized high productivity, with styrene monomer purity equivalent to that of virgin material (up to 99.8%), and a yield rate of approximately 98%, which corresponds to the amount of styrene monomer recovered when one ton of waste polystyrene is fed into the platform. Michelin (France) has prototyped four tons of styrene-butadiene rubber using 100% of their recycled styrene monomer and confirmed that there is no difference in performance compared to rubber used in tires made from fossil-fuel-derived styrene monomer. Tire prototypes and their performance evaluations for trucks' application are planned in the future.

(2) METAL SMELTING

The term "metal production" includes many different processes from mining and smelting to implementation as a product, depending on the sort of metal. This section describes the processes on steel and lithium in particular.

In the move to become carbon neutral by 2050, the steel industry was identified at an early stage as a high

GHG emitting industry. As a result, there is a high awareness of emission reductions in this sector, and technology development is particularly active in Europe. C-Tech Innovation (UK) is in charge of microwave reduction testing in the H2DRI project to develop direct hydrogen reduction technology for iron. The test uses a microwave reactor called a hybrid kiln with a processing capacity of 1 ton/day, equipped with a microwave oscillator with a frequency of 2.45 GHz and an output of 2 kW developed by the company. In collaboration with Rio Tinto (UK), Metso (Finland) is developing the BioIron process in a laboratory in Frankfurt. This uses agricultural residue biomass as an alternative to coke and heats it with microwaves. Metso has demonstrated the process on a small scale with ore from the Pilbara region in Australia. The company is currently working with the University of Nottingham on scaling up to a processing capacity of 1 ton/hour.

The environmental impact of the mining and ore processing of lithium is receiving increased attention due to the growing demand associated with the electrification of energy and transportation, as well as the increased awareness of sustainability throughout the supply chain. Microwave Chemical is developing low-carbon lithium ore smelting technology in collaboration with Mitsui & Co. This development aims to reduce the carbon footprint of the sintering process[4], which is the largest carbon dioxide emitter in lithium smelting. In addition, the National Institutes for Quantum Science and Technology (Japan) are developing a technology for the dissolution of spodumene concentrate[5], and estimate that it can reduce capital expenditure (CapEx) and operating costs (OpEx) by 70%, respectively, and CO_2 emissions by 90%, compared to existing technologies.

(3) METAL RECYCLING

With regards to metal recycling, in addition to technologies for efficiently extracting useful metals from residues such as blast furnace slag and electric arc furnace soot and dust from existing metal manufacturing facilities, microwave reactors are also being considered for use in processes to separate and recover metals from products that consumers have finished using.

The University of Oulu (Finland) reports that when blast furnace slag is irradiated by microwaves and heated at 800°C for 10 minutes, 86% of the zinc contained (among approximately 1% in the slag) can be recovered, and that reuse of blast furnace slag can be explored. Ritsumeikan University (Japan) also reports that while conventional electric arc furnace treatment can recover only 40% of the total zinc contained in ore, microwave irradiation of electric arc furnace dust can recover further 40%, bringing the total recovery rate to 80%. Ritsumeikan is also studying battery recycling, and has confirmed that cobalt metal and lead can be obtained by irradiating the cathode material of lithium-ion batteries with microwaves for a few to a few tens of seconds.

FUTURE PROSPECTS

(1) SCALING-UP OF SYSTEMS

As with general materials development, scaling up for commercialization is a major challenge. Compared to chemical synthesis or recycling processes, metal smelting in particular requires a scale one to two orders of magnitude larger in terms of throughput and processing speed. This increases the difficulty of scaling up. The large size of microwave reactors has conventionally been considered a bottleneck to commercialization. However, in addition to improvements of the equipment, companies are accumulating expertise in parallel processing, which is performed by arranging a large number of modularized apparatuses in parallel. As an extension of these technologies, a future is on the horizon in which large systems that are different from the huge conventional smelting facilities will be launched.

[4] A process to obtain lithium carbonate, lithium hydroxide, etc., which are used in battery materials, from ores by heat treatment. One example is the pyrolytic decomposition of spodumene ores at 1,050 to 1,150°C to convert them into a crystal structure that is soluble in sulfuric acid.

[5] Ore containing lithium and aluminum silicate minerals (spodumene), mainly produced and selected from mines in Australia

(2) SYSTEM DECENTRALIZATION

With the development of the circular economy and the growing importance of economic security, products discarded by consumers are becoming an important resource for new products. From the perspective of the transportation cost and environmental impact of collecting waste from consumers, it would be more appropriate in some areas to install small, modularized equipment near collection sites rather than huge manufacturing facilities to cover large areas. In such cases, decentralized systems will likely proliferate. The collection and analysis of data on the economics and environmental impact of equipment size and waste collection will be essential to determine whether larger or decentralized systems are more appropriate.

(3) POTENTIAL FOR NEW MATERIAL DEVELOPMENT

The use of microwaves of specific wavelengths and the behavior of molecules that they interact with, such as organic synthesis using microwaves, was intensively investigated in the early days of microwave technology. As microwave oscillators become more widespread and less expensive, costs for new material development and manufacturing using such microwave technology will also decrease. The development of new materials will become more active in the future, potentially providing opportunities to commercialize materials that have not been cost-effective to produce.

TECHNOLOGIES TO WATCH IN 2024 — INTELLECTUAL PROPERTY REPORT —

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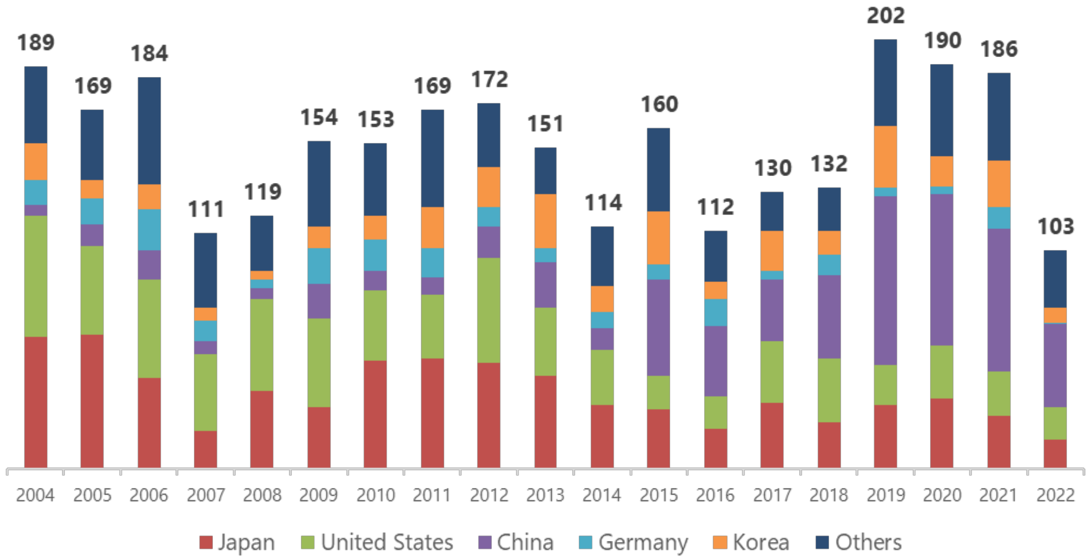
This paper examines, analyzes, and reports on international trends in patent applications related to microwave reactors, which were featured in Technologies to Watch in 2024. This investigation and analysis were conducted using PatSnap Analytics, a global patent search and analysis tool, and PatSnap Discovery, a search tool for various kinds of technical information, provided by PatSnap. All data was obtained on December 1, 2023.

MICROWAVE REACTORS

Figure : Trend in the Number of Patent Applications for Microwave Reaction Devices



Source: Prepared by Mitsui & Co. Global Strategic Studies Institute based on PatSnap Analytics data

ANNUAL TRENDS IN PATENT APPLICATIONS

The number of patent applications for microwave reactors changes by year, with a particularly noticeable increase from 2019. By country, the number of patent applications from Japan peaked in 2004 to 2005 and has been on a downward trend since then. The number of patent applications from the US has also been declining overall, with a particularly marked decrease since 2015. In contrast, the number of patent applications from China has increased significantly since 2015, reaching a record high in 2019.

Accordingly, the 2019 peak in overall applications can be attributed to the sharp increase in the number of patent applications from China. In the 2000s, Japan and the US led patent applications in this area, however, since 2019, China has taken the lead. Note that although the graph shows a significant decrease in the number of patent applications in 2022, it is necessary to take into account the time lag between when a patent application is filed and when it is published. Based on data, the final number of patent applications in 2022 is projected to be approximately 159.

TECHNICAL FOCUS

The data on patent applications for 2019 and beyond were analyzed for technical focus.

The technologies and fields of application are mostly related to microwave reactors, methods, and systems, however, also include industrial applications (metal processing, ceramics production, etc.), chemical research (acceleration of chemical reactions, etc.), environmental technology (waste treatment, etc.), and various other fields.

Regarding equipment and methods, attention has focused on techniques to improve the efficiency and uniformity of microwave heating. This includes adjustment of microwave frequency, optimization of energy distribution, and improvement of energy transfer to the heated object. Attention has also focused on energy-efficient methods and environmentally conscious approaches, such as microwave reactors with energy-saving designs and microwave heating systems using renewable energy sources. Technology to enhance safety and control of microwave heating processes has also been emphasized, including the development of safety devices to prevent microwave leakage and advanced control systems to improve process accuracy and reproducibility.

From this analysis, it is clear that patent applications for microwave reactors focus on heating efficiency, energy consumption, safety, and technological advances in specific application areas. In particular, the interest in energy efficiency and sustainability is indicative of a trend toward the development of environmentally friendly technologies.

REPRESENTATIVE PATENT APPLICANTS

1. Sichuan University (China): Optimization of microwave heating for specific materials and low cost and efficient heating solution.

2. Microwave Chemistry (Japan): Waveguide technology, control of microwave irradiation, acceleration of chemical reactions, and improvement of energy efficiency.

3. Applied Materials (US): Precision microwave technology for semiconductor manufacturing.