Recovery of Metals and Rare Earth Elements by Microwave heating Technology-- A Review

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Abstract

Microwave heating technology is considered one of the most likely to replace traditional heating methods due to its efficient, quick, and green heating transmission that meets the requirements of sustainable development. Microwave heating can strengthen chemical reactions and change the morphology of minerals, and it can save energy and achieve rapid and efficient heating, clean production, and emission reduction. Therefore, this paper summarizes the research status of microwave heating in the recovery of valuable metals (Cu, Au, V),) from metallurgical waste and rare earth elements from rare earth minerals in recent years, expounds the principle of microwave heating, and summarizes the previous experimental phenomena. Finally, the development potential, opportunities, and difficulties of microwave technology in future industrial applications were discussed.

Keywords: Microwave heating; Cu; Au; V; Rare earth.

1. Introduction

Metal is the most important material basis of human civilization, especially agricultural civilization and industrial civilization. Since the Bronze Age, it has been an important material in the production of tools and weapons, and the production and application of metals determine the developmental level of social productive forces (Fieschi and Bianucci, 2015). However, with the unreasonable development and utilization of global mineral resources, not only lead to more and more low-grade ores but also produce a large number of complex waste mineral resources, although the recovery technology continues to progress, due to high recovery costs, complex technological processes and other reasons. At present, a large number of valuable metals contained in low-grade ores and waste resources still can not be effectively recovered (Paraskevas et al., 2015; Reck and Graedel, 2012). Considering that valuable metals are non-renewable resources, if valuable metals can not be recovered economically and effectively from low waste mineral resources, with the development of the global economy and the increase in demand for valuable metals, there will be a shortage of valuable metals, which will leads to a rapid rise in prices (Oguchi et al., 2011).

Furthermore, saving resources and protecting the environment are the basic national policy in China; hence, the process of recycling waste resources must meet the requirements for sustainable green development. The high efficiency of metal resources should be achieved while their economic recovery emphasizes environmental protection (He et al., 2019). Therefore, a new process is needed to achieve economic environmental protection and efficient recovery of valuable metals from waste resources (i.e., low-grade minerals, secondary waste resources) and to improve product quality and environmental protection.

Currently, the methods used to enhance the recovery of rare resources include microwave strengthening (Mahapatra et al., 2019), ultrasonic crushing strengthening (Li et al., 2014; Zhang et al., 2017), electric field strengthening (Peng et al., 2015) and magnetic field strengthening (Veit et al., 2005). Compared with other strengthening methods, microwave heating is a more recent method that can not only strengthen the chemical reaction but also has the potential to replace conventional heating (Chen et al., 2017; Falciglia et al., 2018). It can also be used as an efficient and environmentally friendly heating method (Guo et al., 2020a). Hence, it has attracted the attention of many researchers.

A microwave is an electromagnetic wave with a frequency of 0.3–300 GHz and a wavelength of 0.1–100 cm. Currently, microwaves are widely used in power transmission, radar, communication, and other fields. In the chemical industry, microwave heating technology has received widespread attention for organic and inorganic synthesis (Clarke et al., 2007; Nuchter et al., 2004; Zhang et al., 2003; Zhang et al., 2007), contaminated soil remediation (Liu and Yu, 2006; Yuan et al., 2006), the polymerization process (Ai et al., 2005; Horikoshi et al., 2003), chemical catalysis (Correa et al., 1998; Nuchter et al., 2004), analytical chemical extraction (Prevot et al., 2001; Srogi, 2006), etc. In addition, with the global environmental protection organizations and governments' attention to green chemistry, the improvement of environmental awareness, and the increasing demand for resource reuse, the microwave has been gradually applied to the recovery and utilization of valuable metals and rare earth elements from low waste resources.

This paper reviews some achievements of microwave heating in the field of valuable metal recovery. Emphasizing the microwave process, it explains the characteristics and advantages of the microwave process and compares it with traditional processes. Additionally, the principle of microwave heating is briefly introduced. Furthermore, the applications of microwaves in the extraction of valuable metals from waste resources and their feasibility in the future are discussed, and some suggestions for the further development of this technology are proposed.

2. Microwave equipment and principle

2.1. Microwave device

In general, microwave equipment can be categorized as multi-mode and single-mode, according to the different working modes in the cavity (Cherbanski and Rudniak, 2013; Hoogenboom et al., 2009; Kappe, 2004; Mudhoo and Sharma, 2011; Patil et al., 2014). Single-mode equipment has a smaller cavity and more uniform microwave irradiation and single-mode equipment can be directly focused on a reaction container installed at a fixed distance from the microwave source (Chemat and Esveld, 2001; Kappe, 2004). Besides, the single-mode cavity has better repeatability of chemical experiments, but the single-mode microwave generator has a small amount of single experiment. Hence, multimode microwave equipment is widely used in large-scale experiments because of its large cavity space (Patil et al., 2014).

Commonly, microwave heating devices mainly include microwave generator (magnetron), waveguide, heating cavity, resonant cavity (single-mode or multi-mode), control system, temperature measurement system, as shown in Fig. 1. The microwave is transmitted from the microwave source to the heating cavity by the waveguide.

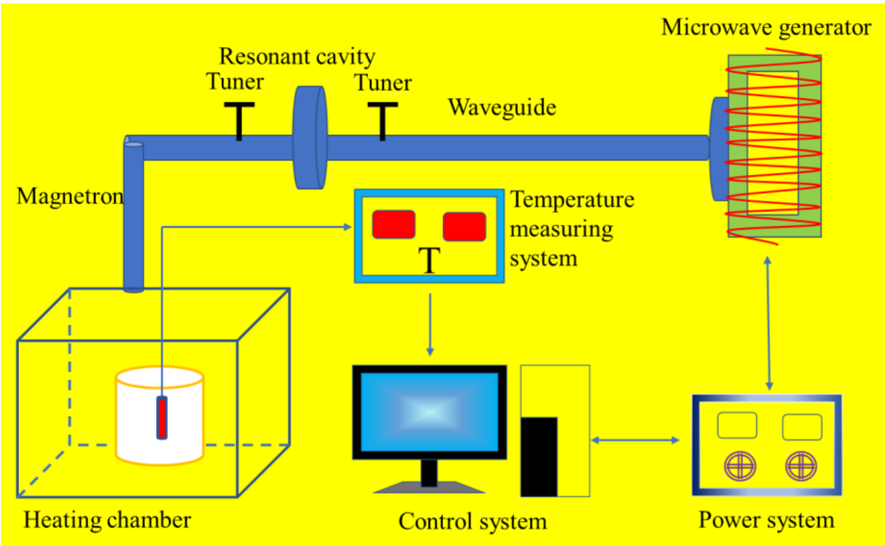

Fig. 1. Schematic diagram of microwave reactor.

2.2. Interaction between microwave and medium

According to different materials, the microwave absorption capacity is also different. generally speaking, there are three forms of interaction between materials and microwaves (Fig. 2): complete transmission (I), complete absorption (II), and microwave reflection and absorption (III) (Huang et al., 2020). In the I form, the microwave passes completely through the material-that is, there is no energy loss when the microwave passes through the material. Such materials are transparent to microwaves and are classified as insulators. In microwave heating systems, insulators are often used as the heating chambers to support the heated materials; these include Teflon, glass, ceramics, and plastics. In the II form, microwaves can be completely absorbed by materials with high dielectric loss; the microwaves cannot penetrate the materials. Materials in the III is microwave reflection and absorption. In the materials, both materials can absorb microwaves completely and materials that can not absorb microwaves, therefore, the microwave will be reflected in the interface between the two materials (Jones et al., 2002).

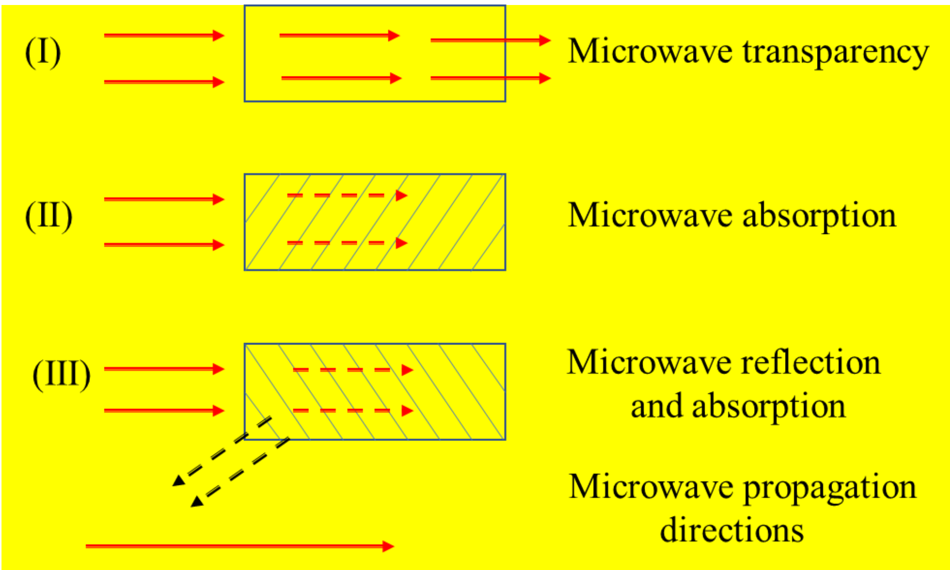

Fig. 2. The schematic diagram of the interaction between materials and microwaves.

2.3. Principle of microwave heating

According to Maxwell's electromagnetic equation, the electromagnetic field is mainly composed of an electric field (E field) and a magnetic field (H field) (El Khaled et al., 2018). As an electromagnetic wave, microwave also has an electric field and a magnetic field, and the two fields are perpendicular to each other (Sun et al., 2016). Due to the different forms of electric field and magnetic field, the mechanism of their interaction with materials is also different, resulting in different heating methods (El Khaled et al., 2018). The specific heating methods of electric field and magnetic field are presented in Fig. 3.

Currently, the mainstream view is that the two main microwave heating mechanisms are: dipole rotation and ion conduction (Anwar et al., 2015; Prieto et al., 2017). As shown in Fig. 4, polar molecules are sensitive to change in the external electric field in the first mechanism (dipole rotation); polar molecules tend to align with the electromagnetic field, so each change in the electric field leads to the rotation of dipolar molecules. Under an electric field of high frequency (2450 MHz), dipolar molecules oscillate 4.9×10^9 times per second. As a result, the dipole does not have enough time to respond to the friction between molecules caused by the oscillating electric field, further to render the increase of material temperature. The typical polar material is water.

In the ion conduction mechanism, microwave radiation affects the charge distribution in the molecule. Under the influence of microwave electric field, any moving carriers (electrons, ions, etc.) move back and forth in the material to produce current. The collision of a charged species with a neighboring molecule or atom produces resistance, and these induced currents heat the sample. Specifically, the electrons in the carbon material will induce the propagation of current in the same phase as the electromagnetic field in the microwave field. Electrons cannot be coupled to the phase change of the electric field; hence, energy is dissipated in the form of heat. This is the so-called interface effect or Maxwell-Wagner polarization effect (Sun et al., 2016).

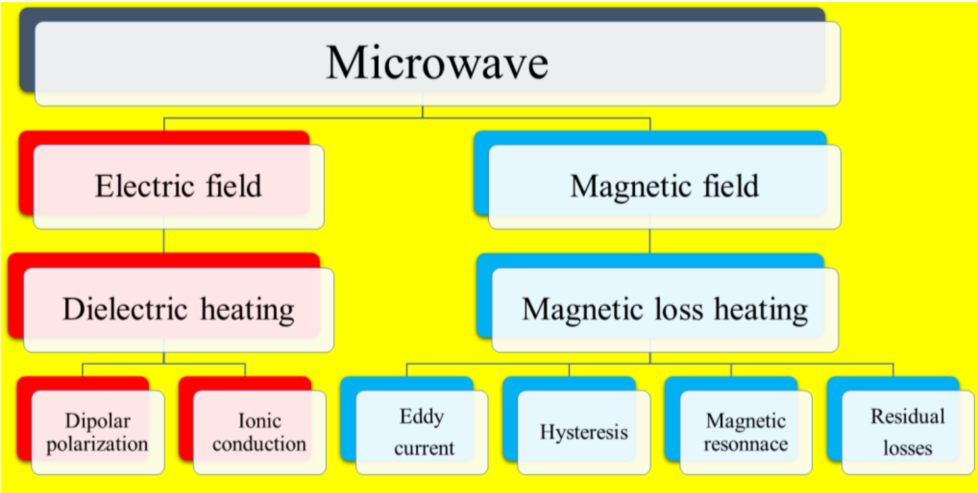

Fig. 3. Interaction mechanism between microwave field and materials.

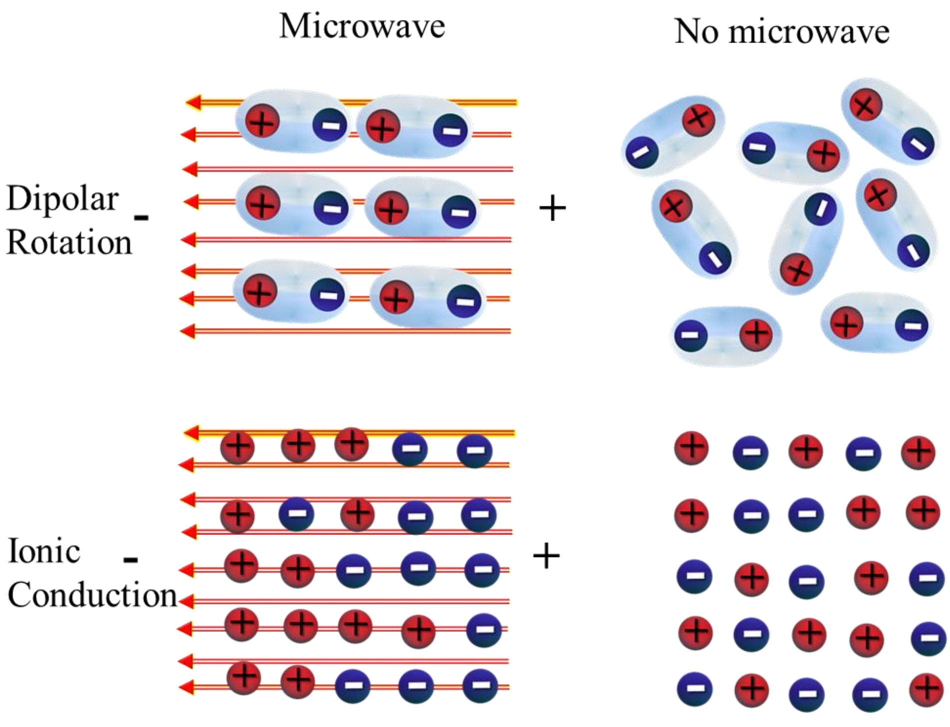

Fig. 4. Schematic diagram of microwave heating principle.

2.4. Advantages and disadvantages of microwave enhanced mass transfer

Compared to conduction heating and convection heating, microwave heating has many advantages (Analia Campanone et al., 2012; Binner et al., 2014; Cheng et al., 2011; Farag et al., 2012; Hesas et al., 2013; Horikoshi et al., 2013; Lin et al., 2015; Oghbaei and Mirzaee, 2010; Zaker et al., 2019). These are shown in Table 1 below.

Table 1. Advantages and disadvantages of Microwave heating.

Microwave heating	
Advantage	Disadvantage
Rapid heating	Temperature rise is out of control
Volumetric and non-contact heating	Addition of microwave receptor is required
Higher electricity conversion efficiency	It is difficult to measure temperature distribution.
Selective: rapid intense heating for polar substances while ineffective for apolar substances	Hot spot: an effect due to inhomogeneity's of Microwave field or dielectric properties within a material, resulting in local temperatures in the material being much higher than the temperature measured in the bulk
Accelerate the reaction speed and shorten the reaction time	Uneven distribution of microwave radiation
The energy input starts and stops immediately when the power is turned on or off,	Dielectric properties change with temperature
Process flexible	Poor security
Environmentally friendly	Low repeatability
Low thermal inertia and faster response	Small processing power
Overall cost-effectiveness/savings	
non-thermal effect.	

3. Application status of microwave in precious metal recovery from secondary resources

3.1. Copper

The excellent properties of copper (Cu) and its alloys make it the first choice for a variety of industrial applications. These properties include high electrical conductivity, thermal conductivity, processability, etc., and have resulted in a significant increase in Cu consumption in recent years. To meet this growing demand, the extraction of Cu has increased rapidly (Jose-Luis et al., 2019). Over just a decade (from 2005 to 2015), Cu production was equivalent to 1/4 of the total Cu mined in human history (Meinert et al., 2016).

A study by Calvo et al. found that the continuous mining and utilization of Cu has led to a downward trend in the grade of Cu ore, which accounts for about 32% of the world's Cu output (Calvo et al., 2016). On average, ore grades fell by about 25% from 2003-2013 that led to a 46% increase in energy consumption for Cu mining(Calvo et al., 2016; Jose-Luis et al., 2019). Therefore, researchers have investigated using microwaves as an enhanced means to achieve environmentally friendly, economy, energy-saving, and efficient recovery of Cu from waste resources.

For example, Moravvej et al. (Moravvej et al., 2018) studied the application of microwave radiation to recover Cu from two main types of Cu ores (oxides and sulfides). Their study showed that when the microwave power is 270W and heated for 15 minutes, the recovery rate of Cu in the ore increased from about 9% to about 23%, indicating a good recovery efficiency;

the study found that the high recovery rate was attributed to the heating crack of the ore caused by microwave irradiation. Sabzezari et al. (Sabzezari et al., 2019) compared the extraction of Cu from the soot of a Cu smelter by conventional heating leaching with extraction by microwave heating leaching. Under the same experimental conditions, the final Cu recovery rate by microwave heating was 11.05% higher than that by conventional heating. The study also found that microwave can effectively remove the ash layer formed by sulfate, which prevents reagents from entering the solid surface and reduce the dissolution of Cu, thus promoting the dissolution of Cu.

Interestingly, in a study on the leaching kinetics of Cu ore, M. Al- Harahsheh et al. (Al-Harahsheh et al., 2005) found that the activation energy (76.5kJ/mol) of microwave leaching of Cu ore was slightly lower than the standard leaching activation energy (79.5kJ/mol), Their findings indicated that microwaves change the reaction kinetics to some extent. Furthermore, mineral particles in a solution are selectively heated with microwaves; that is, microwave radiation caused the temperature of the reaction interface to be higher than that of the solution. This results in local overheating on the surface of solid particles and a higher reaction rate. Moreover, using Cu anode slime as an experimental material, Ma et al. (Ma et al., 2015) recovered all Cu under microwave radiation. They also proposed a view similar to M. Al-Harahsheh - that is, the selective absorption of microwave radiation leads to a temperature gradient caused by overheating of the solid-liquid interface.

Based on this phenomenon, Wen et al. (Wen et al., 2017) further found that microwave-assisted heating can increase the boiling point of the leaching system. They verified that microwaves play a positive role in increasing the reaction temperature of the liquid-solid interface. Additionally, Wen et al. (Wen et al., 2020) studied the modification of the surface structure of chalcopyrite by microwave-assisted leaching, especially in the process of chalcopyrite leaching. The modified chalcopyrite had a larger effective reaction area, active sites, and less passivation layer on the surface. Meanwhile, Lova et al. (Lovas et al., 2003) conducted an in-depth study on the application of microwave heating to the modification of pyrite and found that microwave improved the physical and chemical properties of the effective components of Cu ore. The experiments confirmed the effect of microwave heating on the magnetic modification of Cu ore, the direct effect of microwave radiation on the leaching process of tetrahedral ore, and the positive effect on leaching time.

In brief, the results of microwave recovery of copper from copper ores (oxides and sulfides) show that microwave is an effective means to enhance metal recovery, and microwave heating can effectively remove the ash layer (passivation layer) formed by sulfate in sulfides. Therefore, microwave energy has a great influence in strengthening sulfide leaching, but we should pay attention to the local overheating phenomenon in the reaction process.

3.2. Gold

Currently, gold (Au) resources in the world are increasingly scarce, and Au is a strategic precious metal. The world has mined about 190,000 tons of Au since 1950 (Konadu et al., 2019). However, high-quality ores have gradually dried up, and the remaining Au reserves are only 1/3 of the Au already mined (Ince, 2019). Moreover, due to the low efficiency of extracting Au from ore in the traditional process, a large number of tailings are produced near the Au mine and discarded (Kim et al., 2018). These tailings not only release a variety of toxic substances but also consume a lot of land resources (Quoc Ba et al., 2019). The increased demand for electronic products also aggravates the market demand for Au resources. Therefore, to ensure the reuse of Au resources, an environmentally friendly and efficient recovery process is needed to achieve the economic and efficient recovery of Au from raw ore and other tailings (Guo et al., 2020b).

At present, Su et al. (Su et al., 2011) used microwave to treat low-grade Au concentrate. The results show that the highest recovery of Au can reach 97%, and it is found that the recovery of Au concentrate increases rapidly with the extension of microwave heating time. Zhu et al. (Zhu et al., 2018) used microwave refractory Au cyanide tailings (CT) to achieve low energy consumption and high efficiency to recover Au from Au CT. They also found that substances with stronger microwave absorption capacity such as $CaCl_2$ can aggravate the reaction, which shown that substances with strong microwave absorption capacity can speed up the reaction process and reduce the reaction time.

Li et al. (Li et al., 2020) applied microwave to roast Au cyanide tailings (CT) and found that the highest recovery rate of Au by microwave roasting was 85.2% under the following conditions: a roasting temperature of 1173 K, microwave power of 1300 W, and a roasting time of 15 min. The power and energy consumption of microwave roasting was about half that of conventional roasting. Additionally, microwave roasting reduced mineral toxicity, removed a large number of heavy metals and cyanide, and achieved zero discharge of ore pollutants. These advantages indicated that the industrial application of microwaves in chlorination roasting to extract Au is possible.

Additionally, Zhang et al. (Zhang et al., 2018) studied the decomposition behavior of pyrite in the microwave field using the response surface method. Their results showed that microwave power and irradiation time had a significant effect on the thermal decomposition of pyrite, rendering the smooth and dense mineral surface rough and porous with a wide range of microporous structure networks. This effectively unsealed the encapsulated Au, and the leaching rate of Au reached 91.9%. Similarly, Hu et al. (Hu et al., 2017) reported that the Au originally wrapped in the Au concentrate roasted by microwave has been exposed, and further research has found that the water in the ore sample can also further affect the porosity of the Au concentrate. When the sample with a moisture content of 9% of the Au concentrate is calcined by microwave, it becomes rough and porous, and the specific surface area increases greatly.

Amankwah et al. (Amankwah and Ofori-Sarpong, 2011) found that different substances in Au deposits have different microwave absorption capacities and that the thermal stress produced among the different substances can cause internal cracking of minerals, form microcracks, improve the grindability of the ore, and reduce the crushing strength by 31.2%. Additionally, the leaching rate increased, and the time was reduced by about 10 h. Moreover, Wang et al (Wang et al., 2019). investigated the effect of microwave roasting pretreatment on Au extraction and found that the leaching rate of Au increased to more than 90% after microwave roasting at 500 °C for 30 min. This result was ascribed to the formation of surface cracks, which were beneficial for the migration of thiosulfate leaching agent to the embedded Au. Additionally, microwave roasting reduced the content of organic carbon in the ore.

Thus, it can be seen that the application of microwaves in the recovery of gold can reduce the leaching time, improve the grindability of the ore and reduce the crushing strength. Interestingly, microwave roasting reduces the toxicity of minerals and removes a large amount of heavy metals and cyanide. This indicated that microwave has a potential in the industrial application of chlorination roasting to extract gold.

3.3. Vanadium

Vanadium (V), as an important national strategic resource, is called "vitamin of modern industry" because of its excellent physical and chemical properties and has been widely used in petrochemical, catalyst, iron and steel and other fields (Anjass et al., 2017; Smirnov et al., 2014; Wei et al., 2014), of which the V consumption of the steelmaking industry accounts for 85% of its total output (Moskalyk and Alfantazi, 2003). V titanium magnetite (Janssens et al., 2012) and stone coal (He et al., 2007) are the main V resource in China. At present, sodium roasting technology is the earliest V extraction technology in China (Fig. 5). However, there are serious environmental problems in the process of vanadium extraction. In addition, the problems of sodium roasting method are the low recovery rate of vanadium and high energy consumption (Peng, 2019).

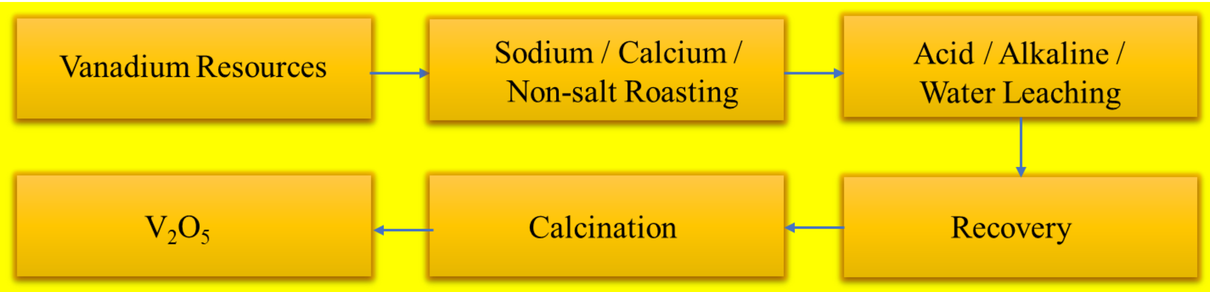

Fig. 5. The traditional vanadium recovery process.

In order to solve the problems of conventional heating, Zhang et al. (Zhang et al., 2020) used microwave-ultrasonic-assisted leaching to enhance the removal of V from petroleum coke. When the ultrasonic power was 1000 W, the microwave power was 500 W, the temperature was 95 °C, the NaOH concentration was 150 g, and the atomic ratio of NaOH to Na_2CO_3 was

3, the leaching rate of V reached more than 90%. These results showed that the contact angle and surface tension between the leaching solution and petroleum coke was reduced and that the leaching efficiency was improved. Gao et al. (Gao et al., 2020) extracted V from high-chromium vanadium slag (HCVS) with the help of a muffle furnace and microwaves. Under the same roasting temperature and roasting time, the oxidation degree of HCVS calcined by microwaves was higher than that of HCVS roasted by muffle furnace, and the extraction rate of V under microwave heating was 98.2% at the optimum temperature of 850 °C, nearly 13% higher than the extraction rate achieved by conventional heating (85.3%). During the roasting process, the excellent heating characteristics of microwaves allowed the material to reach the prescribed roasting temperature in 6 min, thus significantly shortening the roasting time. Compared with conventional heating, microwave heating reduced the particle size of HCVS, while muffle furnace roasting had no such effect.

Yuan et al. (Yuan et al., 2019) optimized the roasting-acid leaching process using the response surface method (RSM). They studied the strengthening mechanism of microwave roasting on Muscovite V oxide, structural deformation by the density functional theory (DFT), and various microscopic characterization methods. Under optimized conditions, the leaching rate of V reached 93.4%. Compared with the traditional roasting-acid leaching process, the introduction of microwaves reduced the roasting temperature by 115 °C, the roasting time by 32 min, the concentration of H_2SO_4 by 10% v, and the leaching time by 4 h. Microwaves also caused the rupture of particles, which had the selective heating effect of promoting low-valent V oxidation, resulting in the expansion of Al-O (OH) octahedral spacing.

Regarding the effect of microwaves on the phase, Tian et al. (Tian et al., 2019) compared microwave heating leaching (MHL) and electric heating leaching (EHL) of converter V slag in an autoclave with an oxygen pressure of 0.4 MPa. Under the same conditions, the leaching rate of V reached 46% under electric heating, while the leaching efficiency of V by microwave heating reached 96% under the same conditions. Their analysis denoted that microwave heating can accelerate the decomposition of the spinel phase in converter V slag, reduce the particle size, and make the particle surface looser. While pressure leaching converter V slag, MHL (14.8 kJ/mol) had lower activation energy than EHL (40.5 kJ/mol) and leached converter V slag more effectively.

3.4. Rare earth

On the periodic table, the so-called rare earth elements include 15 metal elements in the lanthanide elements, as well as the chemically similar yttrium and scandium (Fig. 6). These elements are usually divided into two different subgroups: “light” rare earth elements (LREE) and “heavy” rare earth elements (HREE) (Demol et al., 2019). Rare earth elements are indispensable strategic metals for modern defense systems, electronic applications, and the development of green technologies. The growing economic and strategic importance of these industries, as well as the uncertainty of the global supply of rare earth elements from China, has led to the concerns in various countries about the future supply of many of these metals, including the United States, the European Union, and Canada (Marion et al., 2020). Therefore, improving the development and recycling of rare earth resources is becoming more urgent. Currently, the traditional roasting leaching process (Fig. 7) requires a relatively large number of reagents and special properties and relatively high-cost reaction conditions, and it lacks the selectivity of traditional heating for the decomposition and leaching of rare earth resources (Zhang and Edwards, 2013). Therefore, microwave with selective heating characteristics has become a new and promising research field in the recovery and utilization of rare earth (Xue et al., 2019).

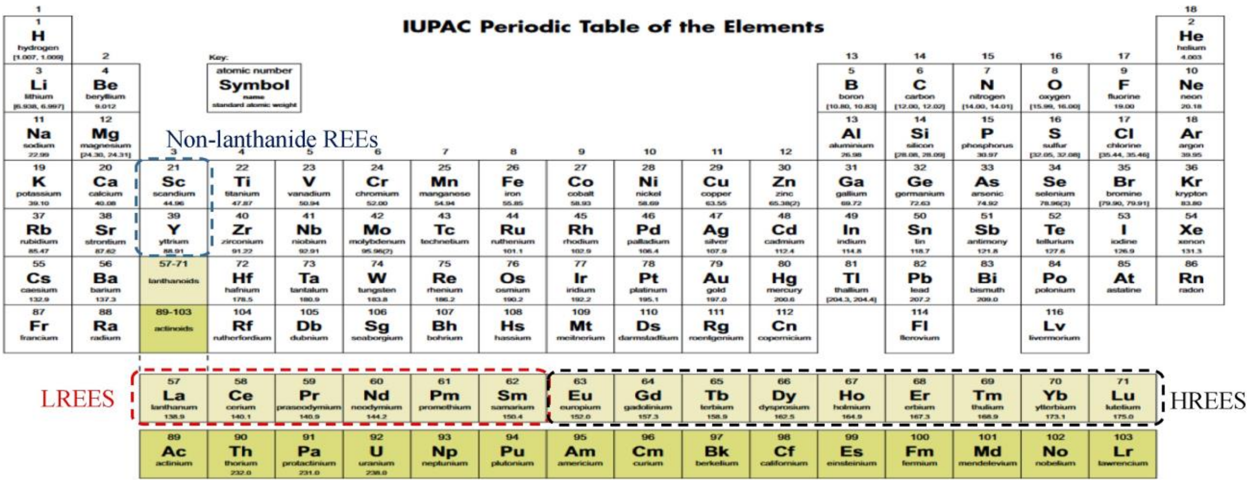

Fig. 6. Distribution map of scandium, yttrium, light rare earth elements (LREE), and heavy rare earth elements (HREE) (Omodara et al., 2019).

Yang et al (Yang et al., 2020). reported that by doping ferrous metal compounds into rare earth, rare earth resources with low absorbing properties can show good absorbing properties in the range of high-frequency microwave. Therefore, the industrialization of microwaves is further promoted by adding additional additives with high absorbing properties.

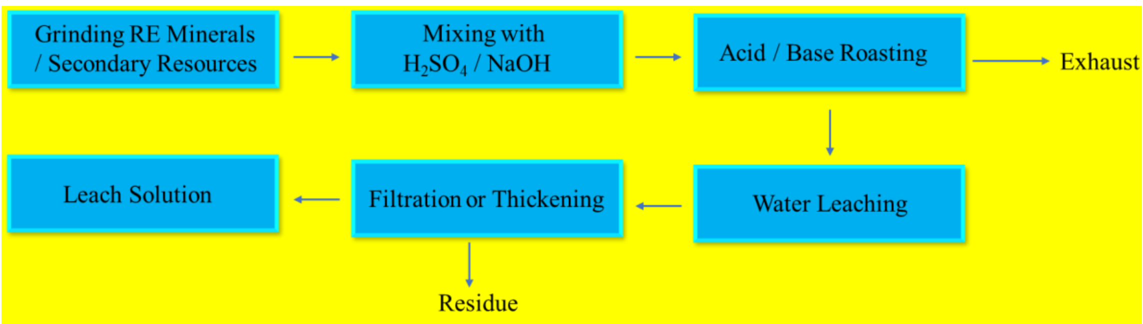

Fig. 7. Typical process flowsheet for sulfuric acid treatment of a rare earth mineral concentrate (Demol et al., 2019; Zhang and Edwards, 2013).

Suoranta et al. (Suoranta et al., 2015) used microwave-assisted extraction to recycle Pd, Pt, Rh, and Ru, as well as cloud point extraction using 1 m hydrochloric acid at 120 ℃. The recoveries of Pd, Pt, Rh, and Ru were 91%, 91%, 85%, and 66%, respectively. Additionally, the concentration of matrix elements (Al, Ce, Zr) decreased by more than 95%. Meanwhile, Huang et al. (Huang et al., 2016a) proposed a new process to treat mixed rare earth concentrates with microwave radiation. They studied the effects of microwave heating on the decomposition mechanism, microstructure, fluorine leaching behavior and hydrochloric acid leaching of mixed rare earth concentrate during this process. The results showed that the phase transformation of rare earth minerals occurs after microwave irradiation. Furthermore, bastnaesite and monazite are effectively decomposed into rare earth oxides by microwave radiation, while fluorinated compounds are converted into fluoride. The recovery of fluorine in leaching concentrate water and hydrochloric acid solution is 67.1% and 82.5%, respectively. These recoveries are much higher than those achieved by a conventional heating method (38.5% and 44.4%, respectively).

Lambert et al. (Lambert et al., 2018) used secondary resources to recover rare earth elements (about 0.03–0.4 wt%) and performed leaching experiments at different microwave powers (600–1200 W). The leaching rates of Nd, Y, and Dy reached 80%, 99%, and 99%, respectively. Further examination showed that gypsum produced cracks and pores in the particles at low power (600 W), which enhanced the penetration of bleaching agents and transformed the gypsum into insoluble crystals. However, high-power microwave heating leads to the thermal degradation of Phosphogypsum (PG) particles and the release of rare earth and changed the crystal structure of PG to a phase, which was difficult to dissolve.

Huang et al. (Huang et al., 2019) studied the phase transition mechanism of mixed rare earth concentrate and sodium hydroxide in a microwave field and found that the decomposition reaction of mixed rare earth concentrate in a microwave radiation field can be divided into three stages. The rare earth elements originally existing in fluorocarbon cerite and monazite were gradually transformed into rare earth hydroxides ($RE(OH)_3$), rare earth oxides (RE_2O_3), and complex oxides ($Ce_{0.5}Nd_{0.5}O_{1.75}$), and finally formed sodium fluoride. The decomposition rate and fluoride conversion rate of the mixed concentrate reached 88.7% and 89.3%, respectively. In addition, the decomposition temperature of mixed concentrate heated by microwave was lower than that required by conventional heating, which further denoted that microwave heating can reduce the thermodynamic reaction temperature.

Huang et al (Huang et al., 2016b). also provided mineralogical information for microwave heating to improve the leaching behavior of rare earth elements (REE) and explained the relationship among mineralogy, the decomposition process, and the leaching process. They studied the effects of microwave heating temperature, time, and NaOH content (the mass ratio of NaOH to mixed rare earth concentrate) on the decomposition of mixed rare earth concentrate and found that temperature was the main factor affecting the decomposition process. With a microwave heating temperature of 140 ℃, time of 30 min and sodium hydroxide content of 35.3%, the recovery rate of rare earth extracted by hydrochloric acid can reach 93.2%, and a large number of cracks caused by thermal stress and the phase transformation of fluorocarbon cerite and monazite were created. The results show that microwave heating makes the non-porous mixed rare earth concentrate particles show porous structure, the porous structure increases the specific surface area, and the rare earth recovery is improved by promoting the liquid-solid contact reaction in the acid leaching system.

It can be seen from the previous works that the microwave roasting of rare earth ores can promote the phase transformation of minerals, reduce the roasting temperature and change the morphology of minerals. These modifications in the minerals phase and surface lead to promote the recovery of rare earth elements.

4. Challenges

Most microwave-assisted heating processes have been performed on a laboratory scale. Although microwave-assisted heating maintains the advantages of a short metal extraction time and effective heating, expanding these microwave methods to a repeatable, high-quality level is still challenging. The two most critical problems that must be solved in microwave-based research are safety and repeatability. Repeatability requires a suitable system to determine the actual microwave absorption and power of the material, as well as a reliable method to measure and control the temperature of the reaction process.

However, reliable temperature control is usually a key issue in microwave chemistry, and care must be taken in the design and interpretation of microwave experiments to avoid drawing incorrect conclusions about reaction temperature, yield or efficiency without considering local temperature hotspots. Furthermore, simulation experiments must be performed for the type of sensor (i.e., internal optical fiber or thermocouple and external infrared sensor), the installation height of the sensor, whether to use stirring, and whether to place special microwave base material and location.

Moreover, when using high wave-absorbing materials, strong local heating may occur; hence, safety is an important issue. As the material may reach a high temperature in a few seconds, safety precautions must be taken. For example, microwave ovens are equipped with a safety shutdown device. Additionally, the material of the container should be considered to prevent the container from melting or exploding due to high temperatures. Microwave radiation can also be applied at short intervals, intermittent cooling time can be applied to prevent overheating and rupture of the reaction bottle, or active cooling can be used.

5. Conclusion and Future Prospect

Microwave heating has been widely used in the enhanced metal recovery process, whether used alone or in combination with other additive methods, the effect of metal recovery is always satisfactory. Moreover, some important conclusions and prospects of our work are as follows:

1. Compared with traditional heating, microwave irradiation has a unique heating mode-fast, selective, and volumetric heating-that can promote metal dissolution. Therefore, under microwave irradiation, metal recovery from waste resources is more likely.
2. The thermal effect formed by microwave irradiation alone leads to cracks in the material running from the inside to the outside; these are helpful in the pretreatment of solid waste.
3. Microwave irradiation can increase the surface temperature of microwave adsorbents through the “overheating” effect on the surface of the absorbents, which can promote the removal of the passivation layer during the reaction process.

4. Microwave radiation can promote the minerals phase transformation, increase the specific surface area of minerals, and reduce the activation energy needed for the reaction.

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