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Eco-Friendly Technology for Recycling of Cutting Fluids and Metal Chips: A Review

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Recently, as environment regulations have been strengthened around the world, new policies that take the environment into consideration have been introduced in various industries. As a result, to protect against environmental pollution and save resources, eco-friendly technologies have been studied. Especially in the machining and machinery industries, interest in how to handle the recycling of cutting fluids and metal chips has increased because these materials are highly toxic. Cutting fluids increase tool life and productivity by cooling and lubricating during processing. However, cutting fluids and metal chips result in environmental pollution and are harmful to the human body. In order to solve the problems associated with these materials, eco-friendly technologies for the recycling of cutting fluids and metal chips have been proposed by researchers and industrial workers. In this paper, a review of physical, chemical and biological recycling methods for cutting fluids is performed, and research and development in relation to the recycling of metal chips are reviewed. Moreover, companies involved in the recycling metal chips are summarized based on the country of origin. The final part of this paper provides a technical summary of cutting fluids and metal chips according to associated the methods used to recycle these materials.

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1. Introduction

Along with the rapid growth of manufacturing technology, the production of high-quality products has become a very important national strategy that affects national competitiveness. Industrialized countries around the world are spurring research on and the development of new and advanced manufacturing technologies. On the other hand, concerns over and regulations regarding the environment, hygiene and safety are intensifying to protect against environmental destruction stemming from the industrial development without eco-awareness.[1-7] Several countries have also developed their own detailed environmental legislation and safety-at-work regulations. The need to develop preventive eco-friendly technologies to suppress or minimize the generation of processing waste and harmful substances which arise during the manufacturing process is therefore urgent.[8,9]

In the machining and machinery industries, cutting fluids are necessary to cool and lubricate the high-temperature and friction-intensive contact between a workpiece and a cutting tool during the machining process.[10-13] It has been recognized that the effects of cutting fluids are advantageous for the cutting of workpieces. However, cutting fluids and the metal chips that result from the machining process are harmful to humans and the environment.

In general, the metal chip is discharged to the outside from the machining area through a chip-conveyor. However, the discharged metal chip should be moved directly to the chip disposal plant by the person using the cart. Also, if the discharged metal chip is not processed for a long time, a problem of space utilization is caused because the discharged metal chip occupies a lot of space in the factory.

Cutting fluids are the main causes of environmental pollution during the transportation and treatment of cutting fluids. When cutting fluids flow into a river or underground water source due to leakage, they can seriously affect the quality of the water. Most of the companies have left the used cutting fluid for a long time without processing immediately. The cutting fluid that has not been used for a long time causes decomposition by microorganisms and bad smell. Specifically, decomposed cutting fluids cause severe odors and worsen working environments. In addition, cutting fluids and metal chips can cause diseases in operators, including lung cancer and skin diseases.[14]

Methods of treating various solid waste or liquid waste discharged through various processes have been studied. In particular, the

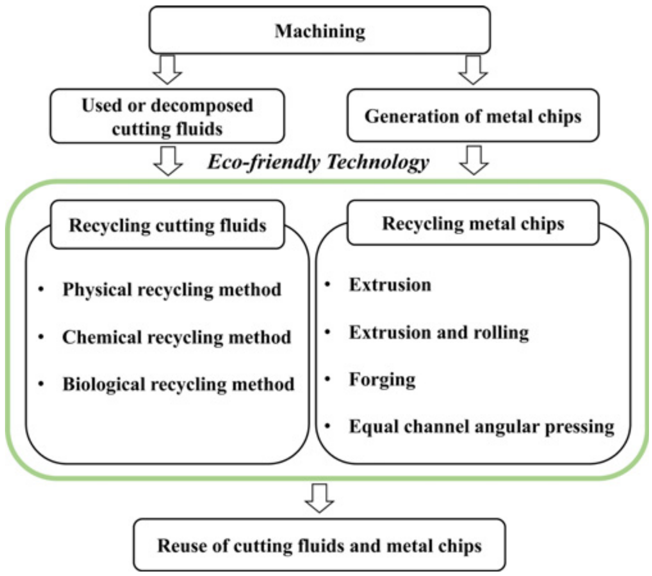

Fig. 1 Eco-Friendly technology system for recycling cutting fluids and metal chips

recycling and disposal of cutting fluids and metal chips can resolve waste disposal problems and environmental pollution problems while also reducing associated costs. Therefore, to address these issues, it is necessary to develop eco-friendly technologies for the recycling of cutting fluids and metal chips, as shown in Fig. 1.[15]

In this paper, the types and characteristics of cutting fluids currently in use and the metal chips present in the fluids are summarized in Chapter 2. In Chapters 3 and 4, physical, chemical and biological methods of the recycling of cutting fluids are reviewed. These chapters also present a review of research and development efforts to create technologies for the recycling of metal chips. The companies involved in the recycling of metal chips are also summarized based on the country of origin. The final part of this paper provides the conclusion and advice on potential future directions.

2. Cutting Fluids and Metal Chips

2.1 Cutting Fluids

Cutting fluids are generally in liquid form; there are many types of cutting fluids, such as chemical fluids, semi-chemical fluids, emulsifiable oils and neat cutting oils. These fluids improve the cutting conditions and lead to higher material removal rates, feed rates, depth of cut, and cutting speeds. Cutting fluids have four characteristics that can affect the machining process.[19]

Functions of cutting fluids

(1) Lubrication

(2) Cooling

(3) Washing away chips

(4) Preventing corrosion

In particular, the most important parameter is the cooling effect, because this can decrease the thermal effect on machined workpieces and cutting tools. Consequently, tool life will be longer because less tool wear will arise. The lubrication effect can reduce built-up edges and can lower the friction coefficient. As a result, the surface roughness improves via the use of cutting fluids during the machining process.[16]

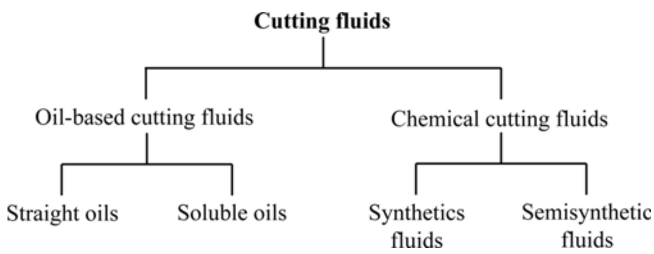

Fig. 2 Classification of cutting fluids

Table 1 Characteristics of cutting fluids[18,19,21]

Type of cutting fluids	Advantages	Disadvantages
Straight oils	Excellent lubricity and easy maintenance	Poor heat removal, Risk of fire, Smoking and misting
Soluble oils	Good lubricity and heat removal	High maintenance cost, Bacterial growth
Synthetic fluids	Excellent heat removal, Microbial control and filterability	Poor lubricity, Misting, Foaming and dermatitis
Semisynthetic fluids	Good lubricity, Heat removal and microbial control	Misting, Foaming and dermatitis

Using cutting fluids is also potentially dangerous. Cutting fluids and metal chips affect both living environments and working environments. The health of machine operators can be impaired when they breathe in or swallow oil mist and/or by skin contact with fluids. Moreover, it is very difficult to dispose of cutting fluids when they are mixed into water. The water and oil phases in the fluids must be separated in order to recycle the water. It is becoming increasingly more important to specify disposal processes for emulsions and waste oils in industry.[17]

2.1.1 Types of Cutting Fluids

Fig. 2 shows the classification of cutting fluids. Cutting fluids are classified into the oil-based and the chemical types. Oil-based cutting fluids can be divided into straight oils and soluble oils. Chemical cutting fluids can be divided into synthetic fluids and semisynthetic fluids. Table 1 shows the characteristics of cutting fluids.[18-21]

2.1.2 Oil-Based Cutting Fluids

Oil-based cutting fluids include straight oils and soluble oils. Straight oils do not contain water; the fluids consist of nearly 100 percent petroleum or mineral oils. Oil-based cutting fluids offer excellent lubricity between the workpiece and the cutting tool. Moreover, oil-based cutting fluids are used for severe cutting operations, such as in the processing of difficult-to-cut materials. On the other hand, straight oils cause a harmful work environment due to misting or the production of smoke and oily films.[22] Soluble oils are commonly referred to as emulsions or water-soluble oils. Soluble oils generally consist of 60-90 percent petroleum, emulsifiers and other additives. The advantages of soluble oils are the good lubrication and

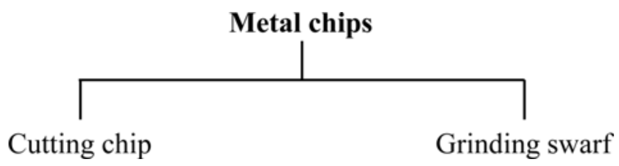

Fig. 3 Classification of metal chips

cooling capabilities they offer given the presence of water and oil. On the other hand, the water in soluble oils can cause bacterial growth, rancidity and oil contamination.[23-25]

2.1.3 Chemical Cutting Fluids

Chemical cutting fluids are referred to as synthetic or semisynthetic fluids. Synthetic fluids contain no petroleum or mineral oils. Synthetic fluids generally contain chemical lubricants and rust inhibitors. The advantages of synthetic fluids are their superior cooling quality and good resistance to rancidity. In addition, synthetic fluids are relatively nontoxic, nonflammable and create no smoke. Although synthetic fluids are less susceptible to the problems of oil-based fluids, there remain several safety and health concerns when using them, such as dermatitis and misting.[26,27] Semisynthetic fluids typically contain 2 to 30 percent petroleum, emulsifiers and water. Semisynthetic fluids are used in various areas of machining and can be maintained easily compared to soluble oils. Moreover, semisynthetic fluids generate less oil mist and smoke and can be more easily used to control bacterial growth and rancidity as compared to straight or soluble oils. In terms of the disadvantages of semisynthetic fluids, these fluids can foam easily due to their cleaning additives, and they typically offer less lubrication than is possible with soluble oils.[28,29]

2.2 Metal Chips

Metal chips occur during every type of machining process, such as milling, turning and facing. Metal chips are generated by the cutting of unnecessary parts using cutting tools with hardness levels higher than that of the workpiece. The shapes of the metal chips depend on the cutting conditions and the materials of the workpiece and the tool.[30]

Fig. 3 provides a classification of metal chips. Metal chips are classified into cutting chips and grinding swarf. In this paper, metal chips are classified into two types depending on the chip size and the processing method.[31]

Cutting chips are generated by the cutting process. The shape of the cutting chip is affected by the material of the workpiece, the inclination angle of the tool, the cutting depth and the cutting speed. Grinding swarf can be generated by any grinding process. The grinding process is carried out by the cutting action of abrasive grains protruding from the surface of the grinding wheel.[32,33]

3. Recycling Methods for Cutting Fluids

3.1 Physical Recycling Methods

All cutting fluids are contaminated by metal chips from the machined workpiece. This contamination has negative effects on the production results. Therefore, separation methods are necessary to produce optimally clean and cool conditions. The main function of a separation method is the removal of particulates. Separation methods include centrifugal separation systems, membrane separation systems and magnetic separation systems.[34-36]

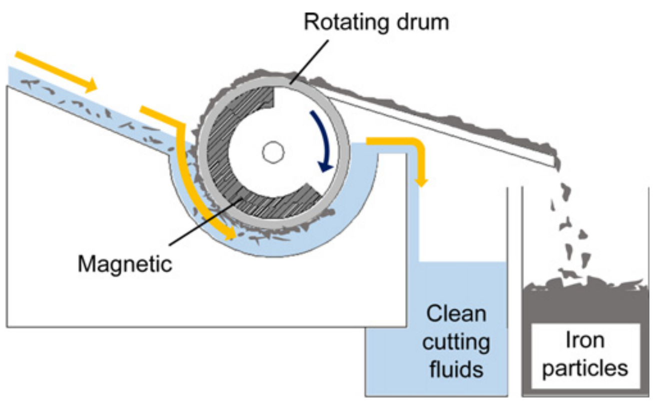

Fig. 4 Magnetic separation system[37] (Adapted from Ref. 37 with permission)

3.1.1 Magnetic Separation System

Fig. 4 provides a schematic diagram of a magnetic separation system. In this separation system, ferrous swarf is attracted to the magnetized surface of a rotating drum for the removal of iron particles, after which the cleaned cutting fluid returns to the machine.[37-39] Chang et al.[40] demonstrated the potential for the immunomagnetic separation of mycobacteria from cutting fluids and compared this method to traditional centrifugation techniques. Nakai et al.[41] developed a high-gradient magnetic separation (HGMS) system using a dry process. One drawback of this method is that powder coagulation causes clogging of the magnetic filter and deteriorates the separation performance of the dry HGMS system. Experiments were conducted to determine the effects of powder coagulation on the separation performance. It was found that particle properties such as the particle shape, cohesiveness and repose angle to have the strongest effects on overall performance outcomes.

3.1.2 Centrifugal Separation System

A centrifugal separation system uses the centrifugal force involved in the spinning of a bowl for contaminant removal, as shown in Fig. 5. Centrifugal force at a high speed pushes the sludge to the outside of the bowl.[42-45] Cambiella et al.[46] studied the effects of several parameters, such as the angular velocity, critical diameter and centrifugation time on the effectiveness of the centrifugation separation system. An oil removal efficiency rate of 92-96% was obtained for all centrifugation experiments. Yamamoto et al.[47] investigated the performance improvement realized after installing a cylindrical blade at the center of the centrifuge to reduce unnecessary space.

3.1.3 Membrane Separation System

Fig. 6 provides a schematic diagram of the membrane separation system. The membrane separation system can separate particulates from cutting fluids using a filter, such as in the ultrafiltration (UF), nanofiltration (NF) and microfiltration (MF) processes.[48-50] Busca et al.[51] undertook the washing cycle optimization of an ultrafiltration plant used to separate waste cutting fluids. As a result, for the greatest

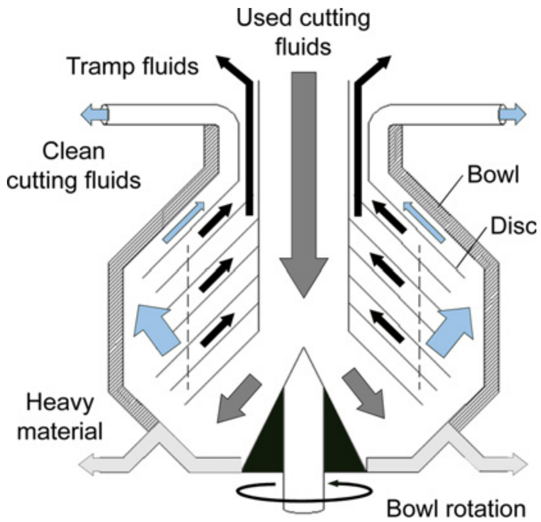

Fig. 5 Centrifugal separation system[47] (Adapted from Ref. 47 with permission)

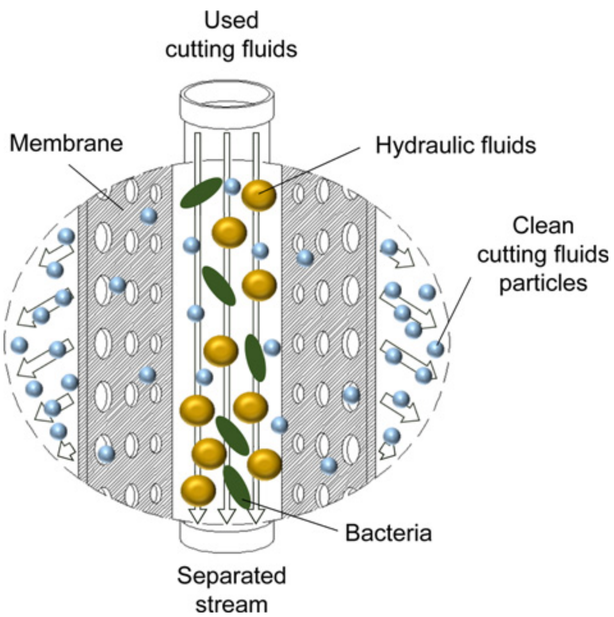

Fig. 6 Membrane separation system[49] (Adapted from Ref. 49 with permission)

outcome during the cleaning of the membrane surface after the filtration of the cutting fluids, the optimal concentration of the surfactant and the temperature of the washing cycle were identified. Muric et al.[52] conducted an experiment to compare ceramic (Al_2O_3 / ZrO_2) and polymer membrane modules for model solutions. The best results were obtained when using reversible ceramic membranes; the membranes are more efficient than polymer membranes.

3.2 Chemical Recycling Method

Chemical recycling methods include two strategies. The first is to use an antimicrobial microbicide. The second is to form recalcitrant molecules. Chemical recycling methods can be most effective when used as a preventive measure.[53,54] Amin et al.[55] studied a recycling method for industrial wastewater contaminated with cutting fluids using a chemical addition-dissolved air flotation (CA-DAF) unit followed by the photo-Fenton process. As a result of an analysis of DAF and the applied photo-Fenton effluents, a 73% removal rate of mono phthalate was confirmed. According to these results, the use of the CA-DAF unit followed by the photo-Fenton process can be said to be practical and effective for the recycling of cutting fluids. Demirbas et al.[56] studied the treatment of cutting fluids by chemical coagulation and electrocoagulation processes. The effects of the operating conditions and the chemical coagulation of the electrocoagulation processes on the chemical oxygen demand (COD) removal efficiency were investigated. Consequently, the COD removal efficiency rates by chemical coagulation from cutting fluids under optimum conditions (500 mg/L of coagulant dosage, 7.5 pH for ferric-based coagulants and 6.5 pH for aluminum-based coagulants) were found to be 97% for alum, 96% for aluminum chloride and 91% for ferric sulphate.

3.3 Biological Recycling Method

Biological recycling methods involve the biodegradation of cutting fluids by microorganisms. Mainly, the cutting fluids are decomposed through mixed or single bacterial strains.[57-59] Jagadevan et al.[60] demonstrated that the effects of ozone and hydroxyl free radicals completely removed cutting fluid components. Their study suggests that a pretreatment with ozone can effectively convert other materials and toxic components in cutting fluids into biochemically resolvable intermediates. As a result, the COD is decreased by 70% relative to its initial value after complex ozone-biological oxidation by an adaptive organism group; 45% of this removal was due to second-stage biological oxidation.

The present authors[61] performed fundamental corruption-prevention experiments on a water-soluble cutting oil using copper alloy. In the results, it was confirmed that when using a filter made of copper alloy, nearly all bacteria could be sterilized after three hours of circulation. Lee et al.[62] studied the antimicrobial effect of copper alloy metal and the prevention of decay of water-soluble cutting fluids as an antimicrobial filter using copper alloy metal fiber. As a result, the antimicrobial effects of copper and copper alloy fiber were confirmed, and the antimicrobial effect of the copper alloy fiber was found to be better than that of pure copper. In order to prevent the deterioration of water-soluble cutting fluids due to decay, the antimicrobial effect of copper alloy metal fiber as an anticorrosive material was also studied. Lee et al.[63] conducted research on maintaining the physical properties of water-soluble cutting fluids using copper alloy metal and investigated property changes due to microbial growth in the fluids As a result of the study, it was found that most of the microorganisms died after ten days when a water-soluble cutting fluid inhibition system using copper alloy metal fiber was installed. It was confirmed that the corrosion of water-soluble cutting fluids due to microorganisms can be prevented by applying copper alloy metal fiber to these cutting fluids.

4. Recycling Methods for Metal Chips

Given recent industrial developments, machine tools have been produced in a technology-intensive form. However, the problem of metal chip processing after the machining of machine tools remains.

Table 2 List of global companies involved in the recycling of metal chips[71-86]

Country	Company	Model	Applicable material	Outputs (kg/hr)	Type	Briquette size (mm)
DE	RUF Maschinenbau GmbH	RAP, RUF Series	Aluminum, Steel, Castings, Copper, Brass, Bronze	30 ~ 4,800	Forging	60 × 40 ~ 150 × 120 Ø60 ~ 150
	WEIMA Maschinenbau GmbH	HD Series	Aluminum, Steel	50 ~ 300	Extrusion	70 × 70 ~ 150 × 60 Ø50
		TH Series	Aluminum, Steel, Castings, Copper, Brass	400 ~ 6,000	Forging	150 × 60 ~ 340 × 340
	PALLMANN Maschinenfabrik GmbH	60 Series	Aluminum, Copper, Magnesium	150 ~ 1,280	Extrusion	Length up to 210 Ø60
NL	STANSZ	MINI – JUMBO Series	Aluminum, Steel	85 ~ 1,375	Forging	Ø65 ~ 225 m
SE	Nederman	BP Series	Aluminum, Steel, Cast iron	100 ~ 800	Forging	Length up to 110 Ø60 ~ 80
IT	CO.MA.FER. MACCHINE	METALPRESS Series	Aluminum, Steel, Cast iron, Copper, Brass, Bronze, Magnesium	50 ~ 2,000	Forging	Ø60 ~ 110
FI	SIMOLIN WATER & ENERGY LTD	SG-16 Series	Aluminum, Steel, Copper, Brass, Stainless steel	300 ~ 5,000	Forging	Ø70 ~ 220
	Metso	ETABRIQ 630	Aluminum, Steel, Cast iron, Copper, Brass	up to 9,600	Forging	60 × 210 ~ 90 × 195 Ø140 ~ 210
US	JOHN HART	COMMAND G Series	Aluminum, Steel, Cast iron, Copper, Brass, Nickel Alloy, Stainless steel	45 ~ 230	Forging	63 × 40 ~ 72 × 40
	ARS	RST Series	Aluminum, Steel, Cast iron, Copper, Brass	34 ~ 1,450	Forging	70 × 76 ~ 90 × 90
	PRAB	MX Series	Aluminum, Steel, Cast Iron, Copper, Brass	57 ~ 2,268	Forging	Ø50 ~ 130
	EMI	BL-500	Aluminum, Steel, Cast iron, Copper, Brass, Stainless steel	1,500 ~ 5,000	Forging	Ø100 ~ 170
JP	AMADA	SCP Series	Aluminum, Mild steel, Casting, Copper, Stainless steel	60 ~ 120	Forging	Ø70 ~ 80
CN	ANYANG	Y83 Series	Aluminum, Casting, Iron, Brass	600 ~ 8,500	Forging	60 × 110 ~ 200 × 250 Ø90 ~ 220
KR	Sammatech Co., Ltd.	GIDEON Series	Aluminum, Steel, Copper	50 ~ 800	Forging	150 × 150, Ø50 ~ 140
	POSSTECH	PCB-150	Aluminum, Cast iron	200 ~ 550	Forging	Ø100

Metal chips generated by machining have a volume which is approximately 15 to 30 times larger than that of the raw material before machining. The shapes and sizes of the metal chips vary depending on the process used. With regard to roughing, the volume of the generated metal chips is nearly 30 times that of the original material; in the finishing process, the value increases by 15 times.[64-67] As a result, the study and development of peripheral devices and systems for machine tools are active. Specifically, metal chip recycling should be studied for the following reasons.[31,68-70]

Recycling of resources

(1) Suppression of environmental pollution

(2) Transportation of metal chips

(3) Maximizing the efficiency of metal chip processing

(4) Metal chip recycling methods are divided into extrusion, forging and equal-channel angular pressing (ECAP). Table 2 shows a list of companies involved in the recycling of metal chips based on the country of origin. The forging method for the creation of metal chip briquettes has been well commercialized in industry.

4.1 Extrusion

Fig. 7 provides a schematic diagram of recycling methods involving extrusion. Extrusion recycling methods involve making the metal chips flow into a die, where they are turned into metal briquettes. Extrusion recycling methods are divided into the cold extrusion and hot extrusion types. Cold extrusion, which takes place at temperatures below the recrystallization temperature, refers to processing below the recrystallization temperature to transform the metal chips into useful shapes; hot extrusion deforms metal chips after heating them to 450 to 550°C in an induction furnace.[87-90] To improve the mechanical properties of the extruded profiles, Guley et al.[91] studied the optimization of the effect of the extrusion die design on the welding quality of metal chips. Metal chips were extruded using flat-face and porthole dies to produce solid rectangular profiles. As a result, extrusion through the porthole die was found to improve the welding of the metal chips, which showed a high ductility of more than 80% compared to that of the profile extruded through the flat-face die. Hu et al.[92] studied the direct recycling of AZ91D magnesium alloy chips by hot extrusion. Microstructural

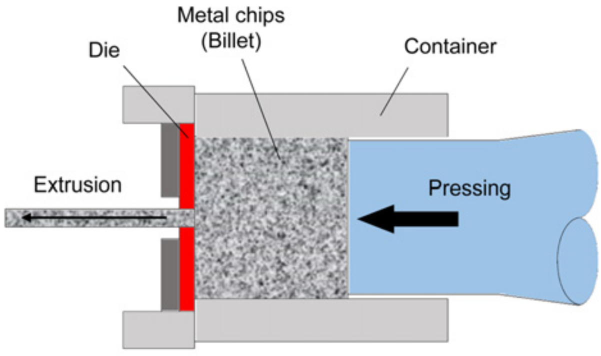

Fig. 7 Recycling method by extrusion[87] (Adapted from Ref. 87 on the basis of OA)

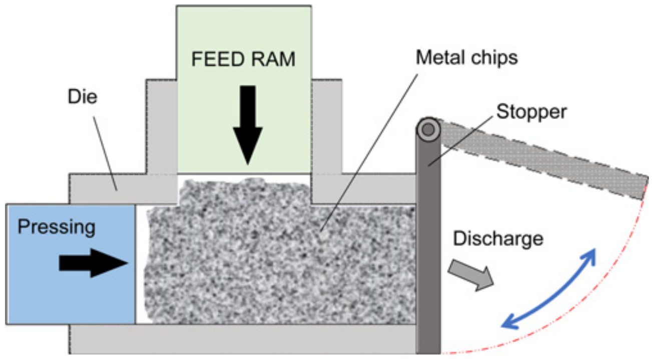

Fig. 9 Recycling method by forging[98] (Adapted from Ref. 98 on the basis of OA)

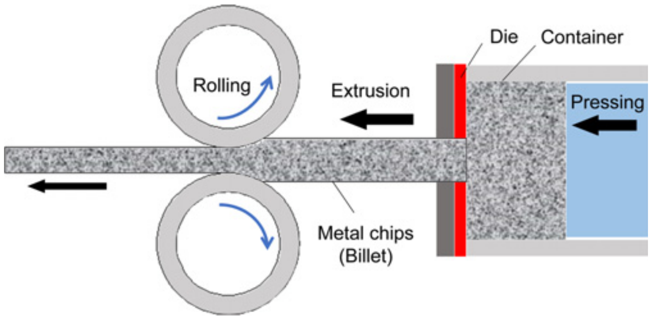

Fig. 8 Recycling method by extrusion and rolling[87] (Adapted from Ref. 87 on the basis of OA)

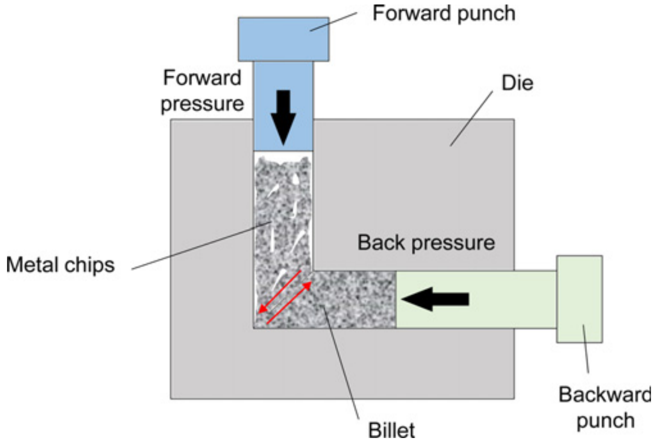

Fig. 10 Recycling method by ECAP[101] (Adapted from Ref. 101 with permission)

analyses were conducted by energy dispersive spectroscopy (EDS), optical microscopy and scanning electron microscopy (SEM) techniques. Consequentially, the material recycled through extrusion showed a high ultimate tensile strength of 342.61 MPa and high elongation at break of 11.32% compared to those values of cast specimens.

4.2 Extrusion and Rolling

Fig. 8 provides a schematic diagram of the recycling method involving extrusion and rolling. The extrusion and rolling recycling method produces recycled sheets by the extrusion and subsequent rolling of the metal chips. The strength and density of the materials recycled through extrusion and additional rolling processes are superior to those of materials recycled using extrusion only.[93] Chiba et al.[94] investigated the possibility of recycling metal chips of Al-Si alloy by cold extrusion with a subsequent cold rolling process. Cold profile extrusion and additional cold rolling of the metal chips produced recycled materials with mechanical properties similar to those of the original ingots. To recycle aluminum alloy cutting chips efficiently, Suzuki et al.[95] studied the mechanical and corrosion properties of hot extrusion with a subsequent hot rolling process. In addition to general rolling, differential-speed rolling (DSR) was applied. As a result, the sizes of the recycled sheets under optimal processing conditions were smaller than those that had not been recycled. Moreover, the mechanical properties and corrosion resistance of the recycled sheets were similar to those of non-recycled sheets. DSR-treated sheets significantly surpassed those that had not been recycled in terms of the tensile properties and corrosion resistance.

4.3 Forging

Fig. 9 provides a schematic diagram of recycling methods involving forging or briquetting. Hot press forging has been used to recycle metal chips. Instead of the conventional methods, hot press forging can be an alternative recycling process for metal chips and can contribute to sustainable manufacturing process technologies in the future. Hot press forging is a simple process without a melting step and is performed above the recrystallization temperature; it is thus beneficial in terms of reduced energy consumption and operating costs.[96,97]

Khamis et al.[98] studied a direct recycling method using the hot press forging process. Metal chips of AA 6061 which were generated by high-speed machining were used, and the mechanical properties of the recycled chips of AA 6061 were studied. With the maximum parameter values, the physical properties of the hot-pressed AA 6061 showed the best microstructure with more grain boundaries due to the high level of consolidation. Yusuf et al.[99] studied the effect of the operating temperature on the direct recycling of aluminum chips (AA 6061) in the hot press forging process. In their results, the grain size at 430°C was found to be coarser because the temperature was lower than the recrystallization temperature. The microstructure changed more finely with an increase in the operating temperature above the recrystallization temperature (above 450°C).

Table 3 Characteristics of recycling methods for cutting fluids and metal chips[40-63,91-103]

Recycling methods			Systems	Capacities	References
Cutting fluids	Physical	Magnetic separation	High-Gradient magnetic separator Immunomagnetic separation	Separable size of particles, 10 ~ 100 μm	Nakai et al.(2010) Chang et al.(2005)
		Centrifugal separation	Centrifugal separator using a cylindrical blade Disc-Stack centrifuge separator	Separable size of particles, 1 ~ 10 μm	Yamamoto et al.(2009) Cambiella et al.(2006)
		Membrane separation	Ceramic and polymeric ultrafiltration membranes Ultrafiltration tubular membrane	Separable size of particles, 0.001 ~ 10 μm	Muric et al.(2014) Busca et al.(2003)
	Chemical		Chemical coagulation and electrocoagulation processes Chemical addition-dissolved air flotation	COD removal efficiency, 78 ~ 99.5%	Demirbas et al.(2017) Amin et al.(2017)
	Biological		Hybrid ozone-biological process Antimicrobial activity of copper alloy metal fiber	COD removal efficiency, 72 ~ 97%	Jagadevan et al.(2013) Lee et al.(2009)
Metal chips	Extrusion		Solid-State recycling of aluminum chips by a hot extrusion process Recycling of AZ91D magnesium alloy chips by a hot extrusion process	Grain size, 12 ~ 200 μm	Guley et al.(2013) HU et al.(2010)
	Extrusion and rolling		Solid-State recycling of aluminum chips by cold profile extrusion and cold rolling Recycling of aluminum alloy chips by hot extrusion and hot rolling	Grain size, 5 ~ 15 μm	Chiba et al.(2011) Suzuki et al.(2007)
	Forging		Sustainable direct recycling of aluminum chips by the hot press forging process Solid state recycling of aluminum chips by the hot press forging process	Grain size, 9 ~ 21 μm	Khamis et al.(2015) Yusuf et al.(2013)
	ECAP		ECAP (metal chips of Ti-6Al-4V) ECAP (metal chips of pure Ti)	Grain size, 0.07 ~ 0.8 μm	Shi et al.(2016) Luo et al.(2013)

Table 4 Merit and demerit of cutting fluid and metal chip recycling methods[40-63,91-103]

Recycling methods			Merit	Demerit
Cutting fluids	Physical	Magnetic separation	Very little maintenance, Low cost, and minimal floor space No filter	Removal of only ferrous or magnetic contaminants Only large particles can be filtered
		Centrifugal separation	Excellent for removal of extraneous oil No disposable filter	A centrifuge may break the emulsion in coarse or weak emulsion products Cannot handle a large quantity of fluid because of the low flow rate
		Membrane separation	Uniform pore structure Bacteria can be removed Compact device Easy maintenance	Slow filtration rate High filter replacement costs
	Chemical		Excellent organic removal rate	Complex processing, Large space is required High maintenance costs Large amount of sludge
	Biological		Good organic removal rate Small amount of sludge	Constraints of working environment Additional equipment is required for sludge processing
Metal chips	Extrusion		Good precision High production speed Low processing costs	Partial crack due to shear stress Dead-Metal zone due to non-uniform flow
	Extrusion and rolling		Excellent precision Dense particle size High productivity	Only simple shapes can be formed Wide facility area is required
	Forging		Complex shapes can be formed Mass production is possible Excellent properties	The cost of the mold is expensive
	ECAP		Ultra-Fine grain size Uniform deformation	Limited processing direction Mass production is impossible

4.4 Equal Channel Angular Pressing (ECAP)

Fig. 10 provides a schematic diagram of the recycling methods involving ECAP. ECAP is a recycling method that transforms polycrystalline general metal materials such as metal chips into ultrafine-grained materials by applying severe shear strain at above an effective strain of 1.0.[100] Luo et al.[101] performed a study to identify the effects of ECAP recycling parameters, in this case the temperature, composition and number of passes, on the strength, ductility and microstructure of recycled Ti. As a result of recycling by ECAP, ultrafine particles were produced at an average size of less than 0.8 μm; moreover, values of 650 MPa for the yield strength and 16% for the ductility were achieved with recycled Ti. Lapovok et al.[102] studied the concept of the compaction of metal chips generated from machining by ECAP. Consequently, ECAP was demonstrated to be an efficient consolidation technology for metal chips of Al and Mg. The best properties of the compacts were obtained for a mixture having a weight ratio of 80% Al and 20% Mg. Shi et al.[103] studied the effects of ECAP process parameters on the relative density, microstructure and microhardness of recycled Ti-6Al-4V. In addition, the microstructure of recycled Ti-6Al-4V was compared with that of the initial metal chips; the evolution of the microstructure according to the number of passes was also investigated. As a result of this study, it was found that when using ECAP operating at moderate temperatures, a fully dense sample (~99.9%) could be obtained with multiple passes at a high back pressure level (100 / 150 MPa). The homogeneity and average hardness were also improved by the multi-pass ECAP method.

5. Conclusions and Future Directions

This paper reviewed research on eco-friendly technologies to recycle cutting fluids and metal chips. Tables 3 and 4 summarize the characteristics of the reviewed recycling methods and the merit and demerit of cutting fluid and metal chip recycling methods. With regard to the physical recycling of cutting fluids, the membrane separation method was found to have the best effects. The chemical recycling method shows better efficiency than the biological recycling method. For the recycling of metal chips, a small grain size is achieved in the order of ECAP, extrusion and rolling, forging and extrusion. The methods for the recycling of cutting fluids and metal chips are economical and environmentally friendly because these methods can reduce the cost of industrial waste treatments as well as the cost of transporting the metal chips. These methods also generate a profit by allowing the sale of metal briquettes made of metal chips and by making cutting fluids reusable.[104] In addition, these methods can solve typical problems of industrial pollution, such as the occurrence of contamination of the work environment and the generation of industrial waste. With the increasing enforcement of environmental regulations in many countries, many people have become interested in technologies to recycle cutting fluids and metal chips, and related studies are being conducted by researchers in many areas around the world.[105]

In the future, the development of hybrid recycling systems (a combination of recycling methods, and a combination of cutting fluid recycling and metal chip recycling) is expected to improve recycling efficiency rates. Furthermore, a system that can integrate eco-friendly technology, automatic control technology and information communication technology and that can allow monitoring in real time will be developed.

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