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# Separation of Emulsified Metalworking Fluid by Destabilization and Flotation

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## Abstract

Metalworking fluids (MWFs) is one among the emulsions widely applied in various industries in machining process. Generally, MWFs consist of oil, emulsifiers, and additives, are used either in the forms of diluted and undiluted fluids. The spent metalworking fluids usually become a very stable emulsion, it requires an appropriate handling procedure. Two typical approaches for dealing with rejected MWFs are recovery and disposal, in which largely involve separation as the first essential step. This chapter presents the topics related to metalworking fluids, ranging from their types, composition, usages, lifecycle, and handling. Afterwards, processes for separating MWFs emulsion are presented, including chemical coagulation, flotation, and electrocoagulation-flotation for their background and results from experiments. Performance in separation, condition, and mechanisms of these three processes dealing with oily emulsion are shown. The understanding in the separation of MWFs by physico-chemical processes can benefit the selection of proper technology for handling of oil emulsion, either generated from machining industries or other activities such as household or petrochemical process.

**Keywords:** metalworking fluid, separation, destabilization, flotation, electrocoagulation-flotation (ECF)

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## 1. Introduction

This chapter covers the contents of emulsion by means of metalworking fluids (MWFs) or cutting oil, which are extensively used in industries. With their compositions, MWFs can form a very stable emulsion during usage resulting in difficulties to deal with, particularly for

separation of the rejected MWFs emulsion [1]. Details on types, properties, usage, and management of spent metalworking fluids are provided. Then, physico-chemical processes for separation are mentioned since separation is one of the critical steps in handling of a stable emulsion for either recovery or disposal [2]. Both theoretical and experimental results with MWFs emulsion are given for chemical coagulation and flotation. Furthermore, electrocoagulation-flotation (ECF), which is an electrochemical system combining the working principles of both coagulation and flotation [3], is presented as another alternative for MWFs emulsion treatment. All these topics could provide the understanding in properties and management of industrial emulsion in the form of MWFs as well as the basis in the handling of rejected MWFs emulsion. Furthermore, it could be applied for separating oil from emulsion generated from other activities.

## 2. Metalworking fluids

Metalworking fluids (MWFs) or cutting fluids refer to various types of fluids that are widely used in machining work for several purposes, for example, boring, drilling, and grinding [4]. With their properties, metalworking fluid can contribute beneficially in machinery processes for: (1) cooling a metal piece at high speed cutting, (2) lubricating the cutting at low cutting speed, and (3) reduce the corrosion rate of a metal surface. Details of metalworking fluid can be exhibited as follows.

### 2.1. Types of MWFs

Metalworking fluids can be categorized based on several criteria. However, since they generally consist of three components including base oil or mineral oil, emulsifiers, and additives [5], the classification based on their compositions is typically applied. Four typical groups of MWFs with different properties and purposes in usage can be summarized as follows [6, 7]:

1. Straight or neat oils are usually used in undiluted form. Their compositions are mineral or petroleum oil and polar lubricants as well as extreme pressure additives, for example, sulfur, chlorine, and phosphorus. This type of MWFs has very good lubricity but relatively limited cooling effect.
2. Water miscible or soluble oils usually consist of oil with emulsifiers to produce stable emulsion for usage. They offer great lubrication and heat transfer performance. Due to its low cost, this MWFs type is most widely used in industries.
3. Synthetic fluids, which are oil-free solution, contain alkaline organic–inorganic compounds and corrosion inhibitor. These oil-free solutions are diluted with water in the range of 3–10% by weight before usage, which provide the best cooling properties among these four types.
4. Semisynthetic fluids or microemulsions are the mixture of synthetic and soluble oils. They offer combined advantages of these oils as good corrosion resistance, lubrication, and contamination tolerance.

In many cases, biocides are added in MWFs for inhibiting bacterial growth under high temperature during operation, which pose a threat in the process performance. Components of metalworking fluids, for example, base oil, emulsifiers, antioxidants, additives, and water, can be greatly varied depending upon the application and required properties during the machining processes [8, 9].

## 2.2. Lifecycle and handling

The lifecycle of metalworking fluids in processes involves four stages, including storage and handling, preparation, usage, and disposal [2].

After usage, MWFs are usually in the form of oil-in-water emulsion contaminated with particulates, metal fines, chips, and tramp oil. They possess high loads of organic components, surfactants, and turbidity [1]. Two approaches are applied with these rejected fluids, including recycling and disposal. In the first approach, contaminants are separated before purifying to recover oil for using in manufacturing process. Separation is carried out via various physical processes, for example, magnetic separation, centrifuge, and filtration. Purification is performed afterwards for adjusting the fluid properties such as heating to reduce viscosity. In addition, sterilization is another process applied for eliminating bacterial growth.

Another approach for handling rejected MWFs is disposal when oil recovering is difficult or incapable of, such as high water content. Moreover, MWFs also lose their properties after usage, which require appropriate handling due to the fact that MWFs waste could be defined as hazardous [10]. Without proper management, this waste can pose severe problems to environment and ecology [11, 12].

## 3. Separation technologies for metalworking fluids

It can be stated that separation plays a key role in MWFs management for both oil recovery and disposal. Separation can be focused on both solid removing from oil waste or oil separation depending upon the selected management approach. Examples of process for solid separation can be displayed as follows:

- Screening: Screens and rotary strainers can trap solid particles larger than 15  $\mu\text{m}$ . This is one of the simplest solid separations based on the retaining principle with the advantages on its high capacity and low cost. The combination with magnetic filters can be equipped for separating metal particles [13].
- Sedimentation: Sedimentation or settling is another simple technique for separating solids by gravity. However, effective removal is limited only for large particles. Moreover, sedimentation demands large tank and long retention time for achieving the considerable performance.
- Centrifuge: This technique uses centrifugal acceleration for promoting the separation; therefore, the unit is much smaller than sedimentation with high removal performance of

small particles. Also, tramp oil can be partially removed by this method. Though, centrifuge consumes high energy, which leads to high operating cost as a result.

- Flotation: Flotation is a physical process employing bubbles for separating fine particles in a dispersed phase. Efficient separation involves the formation of bubble-particle agglomerates those transport particles to the water surface before removing by a skimmer.

After solid removal, another step is carried out for treating emulsified cutting fluids before either discharging to environment or disposal. Many techniques have been applied for this purpose as follow [14]:

- Membrane separation: Ultrafiltration (UF) has been applied to treat spent metalworking fluids. It provides effective performance by separating higher molecular weight compounds (e.g., emulsified oil, fats, and solid components) from lower ones, such as water, dissolved salts, and small organic molecules [15]. The resultant concentrate oil from UF may be processed for oil recovery or incineration.
- Thermal technology: Thermal process for emulsion involves the evaporation of solvents and other solutions with low boiling point. The residue can be oil, emulsifiers, and elements with high boiling point. The main advantage of this method is the great reduction of oil waste volume. Nevertheless, thermal process demands high energy and is suitable for cutting fluid waste with low water content.
- Biological methods: Biological treatment, both aerobic and anaerobic, was reported as an effective treatment for MWFs [16–18], though its applicability covers only low concentration of oil in soluble or emulsified form. The treatment performance by biodegradation for free oil and oil layer/film is limited due to large structure of oil that needs long time for degradation.
- Chemical process: This method is the addition of chemicals those can alter properties of cutting fluid wastes. The main principle is the emulsion breakage by electrolytes to separate between oil and water phases such as inorganic metal salts or acids [19, 20]. This technique is effective to deal with emulsified oil, but has drawbacks on chemical consumption, sludge management, and successive separation united required. Moreover, similar performance can be found from the application of electrocoagulation for cutting fluid treatment [21, 22].

Due to the fact that chemical process plays a key role in the spent metalworking fluid treatment, particular focus should be paid on its mechanisms, which could benefit the process optimization as well as the selection of successive separation unit. The next section of this chapter covers the results of MWFs treatment by chemical coagulation and separation by flotation as one example of MWFs waste handling.

#### **4. Separation of metalworking fluid by coagulation**

Coagulation or destabilization is the process intends to eliminate or minimize the stability of colloidal suspension. It mostly deals with the reduction of electrostatic interaction (repulsion)

among particles in order to promote the aggregation. Mechanisms of destabilization are varied depending upon chemical type, dosage, and conditions, ranging from diffuse layer reduction, adsorption and charge neutralization, polymer bridging, and sweep flocculation, which are the most common mechanisms in water and wastewater treatment. In this part, the results on the destabilization of metalworking fluids are shown with the analysis on the efficiency, optimal condition, and the occurred mechanism.

#### 4.1. Metalworking fluids emulsion

##### 4.1.1. Metalworking fluid

The emulsified metalworking fluid was prepared from commercial cutting oil (Castrol Cooledge BI, Castrol Inc.). It is a soluble metalworking fluid designed for several machining activities, for example, grinding, drilling, and milling. This cutting oil is a mixture of petroleum oil, sulfonic acids, inorganic salts, and organic compounds, such as amide and oil fatty. Characteristics of this oil are summarized in **Table 1**.

##### 4.1.2. Emulsion preparation

The emulsion was synthesized by mixing the cutting oil in deionized water (DI) and tap water at 0.1% w/w denoted as DI emulsion (DE) and tap water emulsion (TE), respectively. This prepared concentration is much lower than the suggested concentration for usage of 3–10% w/w. This concentration was selected to represent the rejected MWFs waste with high water content that limits its recovery. Note that characteristics of both water types were varied on daily basis in a small range of pH, turbidity, and conductivity. The mixture of oil and water was vigorously mixed by a mechanical stirrer at 500 rpm for 10 minutes to form homogeneous milky oil-in-water emulsion.

##### 4.1.3. Characterization

###### 4.1.3.1. Chemical properties

Conductivity and pH of the cutting oil emulsions were measured as displayed in **Table 2**. From its compositions, cutting oil emulsion contained basic properties with pH in the range of 7.5–9.5. The pH tended to be increased with oil concentration in both emulsions, though pH of DE was higher than TE due to the difference in the initial pH of these two water (8.0–8.3 for DI water and 7.2–7.5 for tap water).

Parameters	Test method	Value
Appearance	Visual	Amber/Brown
Density (at 20°C)	Pycnometer	930 kg/m <sup>3</sup>
Surface tension (at 20°C)	Du Noüy ring method	35.2 mN/m

**Table 1.** Characteristics of Castrol Cooledge BI cutting oil.

Parameter	Sample	Concentration (% w/w)							
		0.025	0.05	0.075	0.1	0.2	0.3	0.4	0.5
pH	DE	8.41	8.64	8.79	8.91	9.10	9.22	9.39	9.47
	TE	7.54	7.69	7.82	7.95	8.19	8.31	8.45	8.63
Conductivity	DE	8.8	16.3	22.7	28.6	56.3	88.7	113	142
	TE	243	248	250	252	268	280	293	302

**Table 2.** Chemical properties of the cutting oil emulsions at varied concentration.

Conductivity was analyzed to ensure that the increase of ions in the emulsion merely came from the added cutting oil. As can be seen in **Table 3**, the conductivities were increased with oil concentrations in a linear tendency. The difference of conductivities between these emulsions was only a result of the initial conductivity of DI water ( $\sim 0.9 \mu\text{S}/\text{cm}$ ) and tap water ( $\sim 238 \mu\text{S}/\text{cm}$ ).

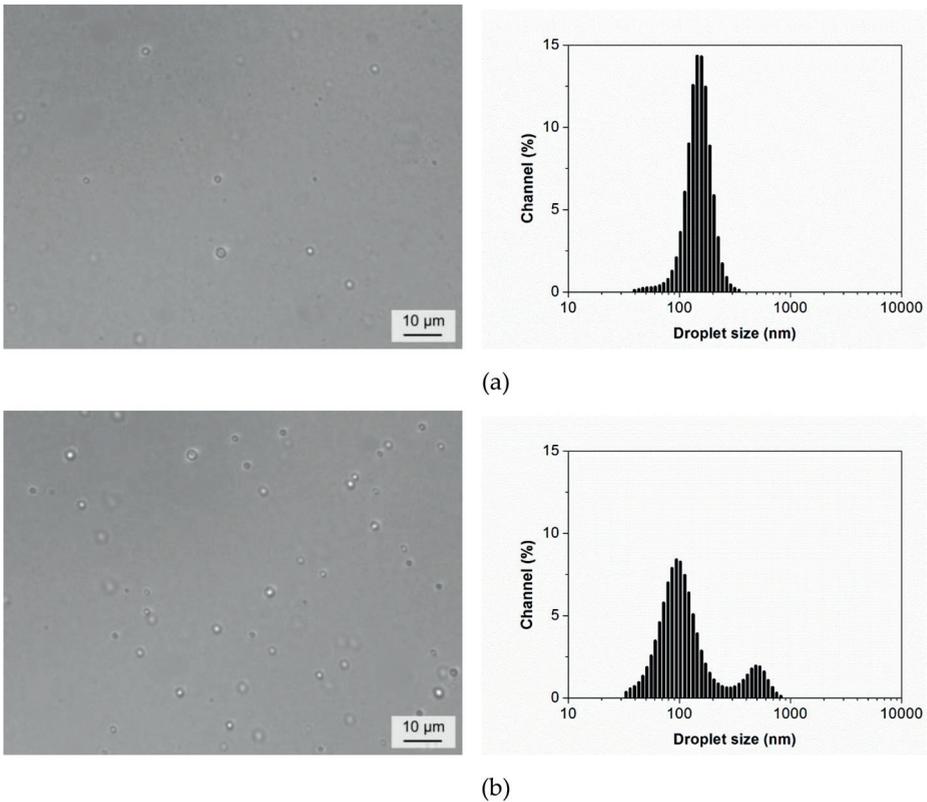
#### 4.1.3.2. Droplet size

Particle or droplet size is the critical parameter to be considered when applying separation process since particles in the same type with dissimilar sizes could act in greatly different ways. Oil droplet size in this study was determined by both visualized and analyzed techniques. The observation of droplets was conducted under an optical microscope with  $40\times$  magnification equipped with digital camera for photo capturing. Droplets can be rarely seen for the emulsion in both water types. The droplet sizes less than  $10 \mu\text{m}$  can be expected. However, oil droplets in TE were easier to be noticed suggesting the presence of larger droplets due to the effects of existed ions in tap water.

The results from particle size analyzer affirmed the finding from observation. Similar results were obtained from analyzers based on laser diffraction scattering (LDS) and dynamic light scattering (DLS) techniques. **Figure 1** depicts the size distribution of oil droplets in 0.1% w/w DE and TE from DLS technique using Nanotracs NPA250 (Microtrac Inc.). The nanoscale droplet sizes in the range of 30–400 nm were found in DE. On the contrary, TE contained larger distribution of particle sizes in the range of 30–900 nm with bimodal distribution corresponding to the presence of aggregates in the emulsion. From the distributions, the average diameter can be calculated in terms of surface-volume mean diameter ( $d_{32}$ ). This type of mean diameter was chosen due to the fact that the value conserves the surface area and volume of

Concentration (% w/w)	0.005	0.01	0.025	0.05	0.075	0.1
DI water emulsion	35.7	71.3	178	368	556	734
Tap water emulsion	42.7	81.4	217	448	656	882

**Table 3.** Turbidities (NTU) of the cutting oil emulsions at varied concentrations.



**Figure 1.** Droplet size distributions of (a) DI emulsion and (b) tap water emulsion at 0.1% w/w oil concentration.

droplets [23]. Both terms are meaningful in the droplet size analysis since the number of oil droplets in emulsion can be changed from shrinkage or coalescence. The  $d_{32}$  of DI emulsion and tap water emulsion can be calculated as 174 and 444 nm, respectively. No difference on size distributions can be seen from varied mixing rate and time beyond 500 rpm and 10 minutes, respectively. Impacts of oil concentrations in the studied range (0.05–0.5% w/w) on droplet sizes were also negligible.

#### 4.1.3.3. Zeta potential

Surface charge is another important parameter for emulsion separation since the existence of electrical charges on droplet surface related to the stability of the emulsion. The surface charge of particles or droplets is generally evaluated in terms of zeta potential ( $\zeta$ ). In this chapter, the zeta potentials of emulsions were examined by Zetasizer NanoS (Malvern Inc.) based on electrophoretic mobility principle. The zeta potential of the DI emulsion was  $-65.8$  mV, which was higher than the tap emulsion ( $-48.4$  mV). Typically, a colloidal nanoparticle system with

$|\zeta| > 30$  mV is considered very stable due to high electrostatic repulsion [24]. Therefore, these emulsions can be classified as stabilized emulsion with negative surface charge. Furthermore, lower zeta potential of TE indicated lower stability of droplets in tap water, which resulted in greater possibility of aggregation corresponding to the microscopic observation of droplets. Ions in tap water could play a role in promoting aggregation of droplets.

#### 4.1.3.4. Concentration

As stated by Byers [25], it is difficult to define the concentration of cutting fluids. Chemical oxygen demand (COD) and turbidity were selected as main parameters as they were suggested as reliable representatives of oil concentration [26]. The prepared emulsions in this study contained the COD in the range of 3000–4000 mg/l, which is commonly found from MWFs containing wastewater from industries [27, 28].

Turbidity is another parameter used for estimating oil concentration. The turbidities of the emulsions were measured by the nephelometric method using a turbidimeter. The results are shown in **Table 3**. A linear correlation between turbidity and oil concentration was obtained suggesting that turbidity can be used for estimating oil concentration. Nevertheless, the turbidity of emulsions at the concentration higher than 0.1% w/w was unable to be measured since the value exceeded the applicable range of the turbidimeter. Furthermore, it should be noted that turbidity of TE was higher than that of DE. This could be the influence of larger droplets or aggregations in tap water emulsion.

From these results, these emulsions of cutting fluids contain nanoscale droplets with high negative surface charge indicating their high stability. As a result, self-separation cannot be expected. Chemical process should be applied in order to destabilize the emulsion before separation. The following sections cover the results of chemical treatment as well as separation by flotation and electrocoagulation-flotation.

## 4.2. Coagulation of metalworking fluids emulsion

Chemical treatment for separating emulsion generally implies chemical destabilization, coagulation, and flocculation [29]. This process does not aim to dispose oil, but to change form of oil to facilitate the separation. Three types of chemicals are commonly used for emulsion destabilization, including acids, metal salts, and polyelectrolytes [20]. In this study, a metal salt, aluminum sulfate or alum, was selected since this coagulant is widely used in both water and wastewater treatments due to its simple application and low cost. Details of experiments and results are as follows.

### 4.2.1. Experimental procedure

Aluminum sulfate ( $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$ ) or alum was used as the coagulant in the standard jar test experiment. The procedure includes the rapid mixing at 120 rpm for 1 minutes followed by 30 minutes of slow mixing at 30 rpm before decantation for 60 minutes. Treated emulsion was collected from the undernatant to analyze for turbidity, zeta potential, and aggregate size as well as observation.

Effects of coagulant dosage and pH on destabilization performance were investigated. Varied coagulant dosages (0.25–2.5 mM Al<sup>3+</sup>) were applied at the pH range of 4–9. In order to determine the optimal dosage of coagulant, the concept of critical coagulation concentration (CCC) was employed. Theoretically, the aggregation of particles begins when the attractive and repulsive forces are balanced due to effects of electrolyte concentration, which can be defined as CCC, where the aggregation of particles changes from reaction-limited to diffusion-limited [30, 31], was applied. The CCC can be determined by the aggregation study with the details on the method can be found elsewhere [32]. Moreover, the efficiency of oil separation was also considered to affirm the optimal dosage obtained from CCC.

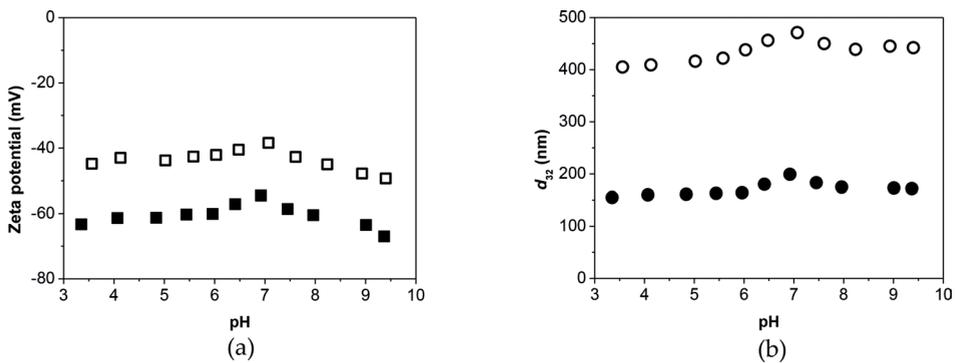
In addition, impacts of oil concentration on the required coagulant concentration were also examined by altering the initial oil concentration in the range of 0.05–0.4% w/w (COD ≈ 1700–15,000 mg/l) at the obtained suitable pH condition. Furthermore, aggregations from each tested condition were sampled for microscopic observation and analysis to determine the occurred mechanism during destabilization.

#### 4.2.2. Preliminary results

Effects of pH on emulsion stability were investigated by adjusting pH by hydrochloric (HCl) and sodium hydroxide (NaOH) solutions without coagulant addition. Only slight change of zeta potential and droplet size can be seen in the pH range of 3–10 as exhibited in **Figure 2**. The largest average droplet sizes in both emulsions can be found at the pH of 6.5–7.5 where the lowest zeta potentials were observed. Nevertheless, these changes in size and stability of droplets were yet sufficient for destabilize and separate the emulsions. Coagulation addition was still required for effective separation.

#### 4.2.3. Coagulation results

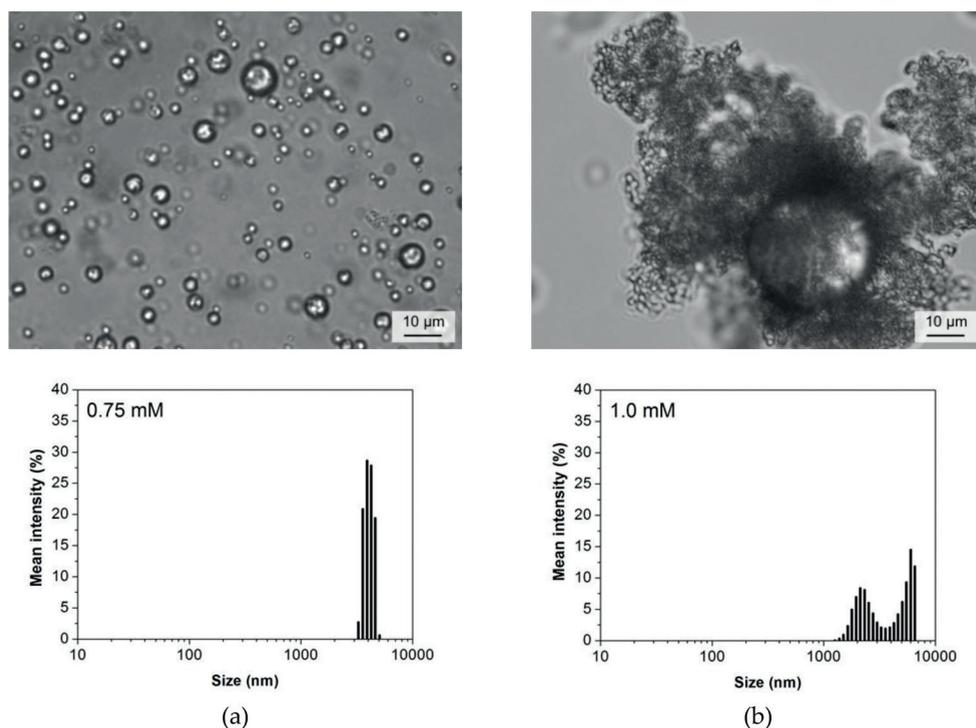
From the aggregation study, the CCC was attained at the Al<sup>3+</sup> concentrations of 0.75 mM and 0.50 mM for DE and TE, respectively. At these dosages, the appearances of both emulsions were highly turbid without the presence of solid precipitates. No separated oil layer can be



**Figure 2.** (a) Zeta potential and (b) d<sub>32</sub> in 0.1% w/w DE (black) and TE (white) at varied pH [33].

observed. Therefore, the separation efficiency was low suggesting the dosage at the CCC might not be the optimal concentration for the effective oil separation from emulsion.

Good separation performance was obtained by increasing the coagulant dosage to 1.0 mM  $\text{Al}^{3+}$  for DE and 0.75 mM  $\text{Al}^{3+}$  for TE. Turbidities of 4–10 NTU can be achieved in the pH range of 6.0–7.5 (efficiency of 95%). Similar efficiency was acquired at higher  $\text{Al}^{3+}$  dosage (1.25–2.5 mM). At this pH range (5–9), solid aluminum hydroxide ( $\text{Al}(\text{OH})_3$ ) is the dominated species apart from free  $\text{Al}^{3+}$  at  $\text{pH} < 5$  and anionic  $\text{Al}(\text{OH})_4^-$  at  $\text{pH} > 9$  [34]. This can explain the observed solid precipitates or flocs in the system, which play a key role in the sweep flocculation mechanism. **Figure 3** expresses the difference in the observed aggregations as well as the size distribution in DE at the  $\text{Al}^{3+}$  concentrations of CCC (0.75 mM) and that achieve the highest separation efficiency (1.0 mM). As can be seen, aggregates at CCC (**Figure 3a**) were only enlarged droplets compared to the initial emulsion with the confirmation from the size distribution analysis. On the contrary, solid precipitates can be seen at 1.0 mM  $\text{Al}^{3+}$ , which corresponded to the two-peak distribution from the size analysis. Note that the zeta potentials of these two dosages were near zero or the isoelectric point. The electrostatic repulsion was reduced to the point that droplets can approach and form aggregates. The effective destabilization in the neutral pH range (5–9) is also found in other works [29, 35]. Similar results were obtained in TE at the dosages of CCC (0.50 mM  $\text{Al}^{3+}$ ) and with the best separation (0.75 mM  $\text{Al}^{3+}$ ). Due to effects of



**Figure 3.** Photos and size distribution of aggregates in DE at (a) 0.75 mM  $\text{Al}^{3+}$  and (b) 1.0 mM  $\text{Al}^{3+}$  [33].

ions in tap water as aforementioned, less coagulant was needed to promote the aggregation corresponding to the initial lower zeta potential of TE than DE. Furthermore, the required dosage of coagulant for emulsion destabilization was in accordance to oil concentration. Due to the fact that surface area of droplets plays an important role in destabilization, higher coagulant was demanded for increasing the MWFs concentration.

Afterwards, flocs were analyzed for its morphology and chemical composition by scanning electron microscope with energy X-ray analysis (SEM-EDX) and Fourier transform infrared spectroscopy (FTIR). The results affirmed the presence of solid aluminum hydroxide ( $\text{Al}(\text{OH})_3$ ) in bayerite structure. The mechanism of sweep flocculation in the destabilization of MWFs emulsion was proved.

Since destabilization is usually combined with other separation process, the understanding in destabilization mechanism is important. Properties of aggregates can affect the flotation performance as well as the operating condition. The results of MWFs emulsion separation by flotation are demonstrated in the following section.

## 5. Separation of metalworking fluid by flotation

Flotation is a physical process using bubbles for separation of disperse phase, such as fine particles or oil droplets, from continuous phase. Its principle is to increase the density difference between phases as well as enlarge the particle size by forming agglomerates with bubbles. By modifying these two parameters, terminal rising velocity of particles can be increased according to Stokes law leading to enhanced separation performance.

Particle separation by flotation involves four steps including: (1) bubble generation, (2) bubble-particle contact, (3) agglomerate flotation, and (4) particle removal by skimming [36]. Generally, flotation performance is mainly controlled by bubble-particle contact. The efficient separation can be achieved by promoting good contact between bubbles and particles. This emphasizes effects of particles' surface property on flotation efficiency. Flotation is widely used in both water and wastewater treatment, especially for removing fine particles. Several gases can be used in flotation depending upon the purpose of application, such as air, nitrogen, fuel gas, and so on. Types of flotation can be classified by bubble generation methods including:

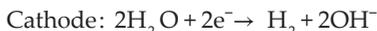
1. Induced gas flotation (IGF): Bubble generation in this process is conducted by agitator or air injection under atmospheric condition. As a result, bubbles in the size range of millimeters are produced. The advantage of IGF is its simplicity, which demands low maintenance and costs for construction and operation.
2. Dissolved gas flotation (DGF): This process is usually employed in water and wastewater treatment due to its high performance. Fine bubbles are generated by releasing the super-saturated water with gas at elevated pressure in the atmospheric condition. Due to the reduction of pressure, the dissolved gas precipitates from water in the form of tiny bubbles with the general sizes of 30–70  $\mu\text{m}$  [37].

Flotation is usually combined with other techniques, chemical process in particular, in order to enhance its separation efficiency, especially in the cases those deal with fine or stable particles. Several works reported the success of flotation application for separating oily emulsion [20, 29, 38]. Flotation was then applied for separating the synthetic MWFs emulsion with and without the addition of coagulant (alum). Air was selected as the gaseous phase in the flotation processes, the so-called induced air flotation (IAF) and dissolved air flotation (DAF). Flotation test was carried out in a column with 0.1 m in diameter and 1.25 m in height. The difference between these processes was the bubble size at which bubbles in the ranges of 0.95–1.40 mm and 48.7–49.5  $\mu\text{m}$  were generated in IAF and DAF, respectively.

It was found that the separation was inefficient without coagulation. The addition of alum can increase the separation efficiency to 85% in the continuous operation. Although the efficiency of flotation with chemical addition was less than only coagulation, it offers the advantage of rapid separation where the highest efficiency can be obtained with less than 10 min compared to 60 min in coagulation. No difference can be seen on the efficiency in IAF and DAF, suggesting small impacts of bubble size on the separation performance. However, the efficiency was governed by coagulation. The results indicate the limitation of flotation in dealing with stable emulsion contains nanoscale droplets. By adding coagulant until the sweep flocculation occurs, droplets are increased in size with less stability that can facilitate the separation by flotation. Also, the single bubble experiment demonstrated the different in bubbles-aggregations contact in the cases with and without flocs. Flocs can adhere to bubble surface in contrast with droplets. Details on the single bubble experiment can be found elsewhere [39]. This finding confirmed the necessity of coagulation in flotation to deal with MWFs emulsion or other stable colloidal system.

## 6. Separation of metalworking fluid by electrocoagulation-flotation

Electrocoagulation-flotation (ECF) is the physico-chemical process based on electrochemical reactions. Main components of this process are electrodes and power supply for providing direct current electricity. The reactions taking place at electrodes are as follows:

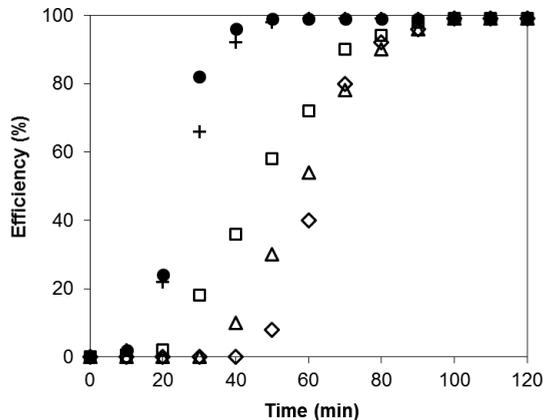


As can be seen, cations produced for coagulation in ECF are dependent on materials of electrodes. Hydrolysis at both anode and cathode contributes to the generation of microbubbles, though majority of bubbles are hydrogen gas ( $\text{H}_2$ ) from cathode. Therefore, coagulation and flotation can occur simultaneously. Furthermore, electroflotation can be performed by using non-sacrificial electrodes such as graphite. In this case, only bubbles of  $\text{O}_2$  and  $\text{H}_2$  are produced to act in flotation.

ECF has advantages over chemical coagulation since no chemical addition is needed as well as the capability to maintain pH during operation. In addition, less sludge volume is produced in ECF as the formed metallic oxides/hydroxides in this case contain less water content than the chemical sludge [40]. However, high power consumption and electrode corrosion is still its main disadvantage as well as the generation of dissolved solid from the operation due to the electrode sacrifice [41].

This process is reported as an effective technology dealing with several types of wastewater, for example, wastewaters from restaurant and textile industries [42, 43]. Also, ECF is effective in treatment of metalworking fluids as reported in several works [21, 35]. ECF was then tested in the separation of the synthetic MWFs emulsion in a 13.5-L bubble column using aluminum as the electrodes. The current density, that is, ratio of electric current to active surface area of electrodes, and electrode gap are varied from 25 to 125  $A \cdot m^{-2}$  and 1–4 cm, respectively. Some of experimental results are exhibited in **Figure 4**.

From the results, it can be seen that the treatment efficiency of ECF can be divided into three stages, including lag, reactive, and stabilizing stages similar to those found in other works [29, 43, 45]. This can be explained by the fact that the hydrolyzed metal ions require a period of time to form flocs those are necessary in the sweep flocculation. Afterwards, the efficiency is dramatically increased until reaching the stabilized stage where the efficiency is constant. The effective separations with the highest efficiencies of 99% were attained from all conditions but at different operating time. The treatment rate was influenced by the condition for both electrode gap and current density. Higher current density results in more liberated metal ions, in other words, higher concentration of coagulant ions; therefore, faster coagulation can occur. On the other hands, electrode gap plays a role in mixing, which has to be optimized to achieve good treatment rate. Short distance between electrodes results in too much turbulence contributing to the flocs breakage. On the contrary, large electrode gap provides



**Figure 4.** Treatment efficiencies at varied current densities and electrode gaps: (◇) 50  $A \cdot m^{-2}$  1 cm, (□) 50  $A \cdot m^{-2}$  2 cm, (△) 50  $A \cdot m^{-2}$  4 cm (●) 125  $A \cdot m^{-2}$  1 cm, (+) 125  $A \cdot m^{-2}$  2 cm [44].

insufficient mixing to promote particles contact for aggregation. Sludge produced from ECF was lower than the alum coagulation around 20% in volume, which can benefit the sludge management in both handling and cost aspects.

## 7. Conclusion

This chapter presents the details of metalworking fluids, which are oily emulsion commonly found as industrial wastewater. Background information and experimental results on separation of MWFs emulsion are provided. It can be suggested that emulsion of metalworking fluids, which is commonly used in machining processes, are stable due to the presence of emulsifiers. Focusing on the disposal, chemical coagulation is needed for achieving efficient separation performance. Furthermore, the considerable performance was also acquired from electrocoagulation-flotation. Destabilization is the critical step for efficient handling of this type of emulsion. The effective separation of MWFs emulsion can benefit the management of spent fluid after usage in order to reduce its adverse effects on environment when discharged as industrial wastewater.

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