Combined physical, chemical and biological treatments of wastewater containing organics from a semiconductor plant

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Abstract

Wastewater containing organics from a semiconductor plant was experimentally investigated in this study. The wastewater is characterized by strong color, high chemical oxygen demand (COD), a large amount of refractory volatile organic compounds and low biodegradability. Because of these characteristics, treatment of this wastewater by traditional activated sludge method is essentially impossible. In the present work, combined physical, chemical and biological methods were synergistically utilized to tackle the wastewater. The combined treatment consisted of air stripping, modified Fenton oxidation and sequencing batch reactor (SBR) method. Air stripping was employed to remove the majority of volatile organic components (notably isopropyl alcohol) from the wastewater, while the Fenton treatment decomposed the remaining refractory organics leading to simultaneous reductions of wastewater COD and color. After proper dilution with other low-strength, organics-containing wastewater stream, the wastewater effluent was finally treated by the SBR method. Experimental tests were conducted to determine the effectiveness and the optimum operating conditions of each treatment process. Test results clearly demonstrated the advantages of the combined treatments. The treatment train was found capable of lowering the wastewater COD concentration from as high as 80,000 mg/l to below 100 mg/l and completely eliminating the wastewater color. The overall water quality of the final effluent exceeded the direct discharge standard and the effluent can even be considered for reuse.
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Keywords: Semiconductor wastewater; Air stripping; Fenton oxidation; Sequencing batch reactor; Chemical coagulation

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1. Introduction

Semiconductor is an important electronic product. It is widely used in computers, consumer electronic products, communication equipment, electronic control devices, and scientific and medical test equipment. Due to increasing demand in recent years, average annual growth of semiconductor industry has been increasing rapidly at a double-digital rate.

The semiconductor manufacturing is a highly complex and delicate process that consists of over a hundred steps of silicon growth, oxidation, doping, photolithography, etching, stripping, dicing, metallization, planarization, cleaning, etc. [1–4]. Over a hundred of different organic and inorganic compounds (proprietary or generic) are involved in the manufacturing process. In a typical semiconductor manufacturing process, a large quantity of ultrapure water is also utilized in the washing and cleaning steps [2,4]. Consequently, a significant amount of wastewater is generated. Direct discharge of the wastewater generated is strictly regulated due to presence of various organic and/or inorganic compounds. The wastewater generated in the semiconductor manufacturing process may contain non-halogenated solvents, acids, bases, salts and other organic compounds [1–4]. A typical semiconductor wastewater obtained from a large manufacturer was strongly colored because of presence of refractory photoresist, solvents, dyes and salts. In addition, the wastewater had a high chemical oxygen demand (COD) concentration, frequently exceeding 50,000 mg/l. Feeding this low biodegradable wastewater along with other wastewater streams to the activated sludge tank places a considerable strain on the biological wastewater treatment system currently employed by all semiconductor manufacturer in Taiwan. To overcome this difficulty and to improve the overall performances of the biological treatment system, separate treatment of this particular high-strength semiconductor wastewater by alternative methods is in order.

Due to the complexity of the semiconductor wastewater, any single treatment method would be inadequate. In the present work, physical, chemical and biological methods are combined in dealing with this wastewater. Combination of physical, chemical and biological treatments can offer significant complementary advantages and are cost effective. More specifically, the combined treatment method employed in this study comprises of air stripping, Fenton oxidation and sequencing batch reactor (SBR) treatment. Air stripping was utilized primarily to recover isopropyl alcohol (IPA), an important solvent used for cleanings in the semiconductor manufacturing process and present in significant quantity in the wastewater. Air stripping adopted in this study may not be as sophisticated and efficient as distillation for IPA recovery, but the apparatus is relatively simple, low cost and easy to operate. The recovered IPA, if sufficiently pure, can be recycled for reuse. Fenton oxidation [5] was intended to decompose the recalcitrant organic chemicals in the wastewater, leading to considerable enhancement of the wastewater biodegradability. In many previous investigations [6–9], chemical oxidation using Fenton reagents have been found quite effective in dealing with various types of industrial wastewaters. In general, Fenton oxidation can be the regular type or its electrochemical variation. In the present work, the regular Fenton oxidation was adopted. The reactor for Fenton oxidation was modified to accommodate temperature control for operation above room temperature. Finally, the SBR method [10–13] was employed as a polishing step to further lower the wastewater COD to the discharge standard. The SBR has been gaining popularity as an

alternative to the conventional activated sludge treatment because of its lower cost, ease of operation, high waste removal efficiency and better capability to handle variable waste load [10–13].

2. Materials and methods

The raw wastewater samples for the present study were obtained from a large semiconductor manufacturer in northern Taiwan. The content of the wastewater was very difficult to ascertain due to the unknown types and amounts of various chemicals (a number of them being proprietary) employed in the manufacturing process. However, according to the plant technical personnel, the raw wastewater samples contained primarily only organics and wastewater streams containing other pollutants (hydrofluoric acid, metals, particulates, etc.) were separately collected. The water quality of the wastewater sample, such as the COD, BOD, SS, conductivity and color (in terms of ADMI), was measured by the standard methods [14] along with a GBC 916 UV-Vis spectrophotometer (GBC Scientific Equipment Ltd., Victoria, Australia). The IPA concentration of the wastewater samples was measured using a HP 5890 II gas chromatograph (Hewlett-Packard, Denver, CO, USA) with FID detector and Restek RTX-5 capillary column (0.53 mm i.d. and 30 m long).

For IPA recovery, a packed-bed stripping column was designed. The apparatus consisted of a pyrex column of 6 cm i.d. and 100 cm long. The column was randomly packed with ceramic Raschig rings (0.8 mm i.d. and 10 mm long) to a height of 45 cm. The Raschig ring packing served to improve the liquid/gas contact and facilitate the IPA recovery. The void of the packed column was determined by the water displacement method to be 0.48. The pyrex column was equipped with an external water jacket for temperature control and during the test runs, desired column temperature was controlled by a constant temperature bath to an accuracy of $\pm 1\,^{\circ}\mathrm{C}$. Since the IPA normal boiling point is merely $82.4\,^{\circ}\mathrm{C}$, the operating temperature for all test runs was kept below that level. A side condenser with an effective cooling length of 50 cm was attached to the top of the packed-bed stripping column. During a test run, constant cooling water maintained at $0\,^{\circ}\mathrm{C}$ ($\pm 0.5\,^{\circ}\mathrm{C}$) was circulated through the external condenser jacket to condense out IPA and the entrained water in the gas mixture exiting the stripping column.

At the beginning of a test run, 1 l of semiconductor wastewater was put in the stripping column, reaching a height of 55 cm. The column was maintained at a desired constant temperature (between 40 and $70\,^{\circ}\mathrm{C}$) as controlled by the constant water bath. It usually took approximately 20–30 min to reach a steady state operating temperature. Air was then let in through the column bottom distributor. During the tests, the desired air flow rate was varied between 1 and 4 l/min. The gas mixture exiting the column from the top went to the side condenser and the condensate was collected. After a test run was started, samples were taken periodically from the bottom sampling port of the stripping column and the collection bottle of the side condenser for IPA measurement. The amount of condensate was registered also. Note that the air stripping was conducted in batch mode for convenience of determining the air flow rate, stripping temperature and time for good system performance.

Fenton oxidation was carried out batchwise in a 3-l pyrex reactor of 13 cm i.d. and 27 cm height. The reactor was equipped with an external water jacket for temperature control.

The thermometer and hydrogen peroxide input were provided in the lid of the reactor. The wastewater in the reactor was maintained well mixed by a magnetic stirrer. At the beginning of a test run, 1.5 l of the wastewater after air stripping were placed in the reactor and the stirrer was set at 100 rpm to keep the uniformity of the reactor content. The wastewater temperature was maintained steadily at a desired level chosen among 25, 50, 70 and 90 °C by the circulating hot water external to the reactor. Ferrous sulfate was added in a single dosage and hydrogen peroxide was fed continuously by a feed pump at an appropriate rate in proportion to the amount of ferrous sulfate. Small amount of sample was taken periodically after a run was started for measurements of COD and ADMI. Various treatment times up to 3 h were tried in the test and 1.5 h was found sufficient to achieve good treatment results in terms of COD and ADMI removal. To facilitate the suspended solids (SS) removal at the end of a test run, chemical coagulation using polyaluminum chloride (PAC) and polymer was adopted. A low dosage of 50 mg/l PAC and 0.5 mg/l polymer was found sufficient to effect an excellent SS removal in less 20 min, as compared to at least 3 h required for natural settling. The wastewater after chemical coagulation was free from any visible color with a very low ADMI in the neighborhood of 10.

The SBR treatment utilized a 15-l cylindrical tank that was equipped with a fine bubble aerator. The effluent from Fenton oxidation had a COD under 700 mg/l and a BOD/COD ratio of 0.38 ± 0.06. The effluent was seeded with activated sludge obtained from the municipal wastewater treatment plant. The seeded wastewater had a mixed liquor suspended solids (MLSS) concentration of 2800 ± 400 mg/l. Ten liters of the seeded wastewater were placed in the SBR tank (the Fill step) and aeration was started immediately (the Aerate step). The air flow rate was kept at 25 l/min which was sufficient to provide good mixing and to maintain a 3–4 mg/l DO in the aqueous solution. The aeration was stopped after for 10 h and it was followed by 1.8 h of sludge settling (the Settle step). The bottom sludge occupied approximately $25 \pm 2.6\%$ of the aqueous volume. Seven liters of supernatant were withdrawn and samples were taken for water quality measurements. This completed a SBR cycle. Equal amount of wastewater was added to start the next cycle. The last two steps (the Draw and Fill steps) were finished in 0.2 h.

3. Discussion of results

3.1. Wastewater characteristics

The organic contents of the raw wastewater samples, as obtained from a large semiconductor plant, were very difficult to identify due to many proprietary and complex chemicals employed in the semiconductor manufacturing process. According to the semiconductor manufacturing process, the wastewater contained varying amounts of surfactants, photoresists (consisting of complex polymers, additives, sensitizers, etc.), developing agents (tetra-methyl ammonium hydroxide, mono-ethanol amine, glycol ether, etc.), stripping agents (2-propanol amine, diethylene glycol mono-methyl ether, etc.), cleaning agents (IPA, N-methyl-2-pyrrolidinone, etc.) and other organics (methanol, alkylene glycol, dyes, etc.). The raw wastewater samples in general had a strong dark color with ADMI of $46,750 \pm 550$ and very low SS concentration less than 10 mg/l. The COD concentration was high at
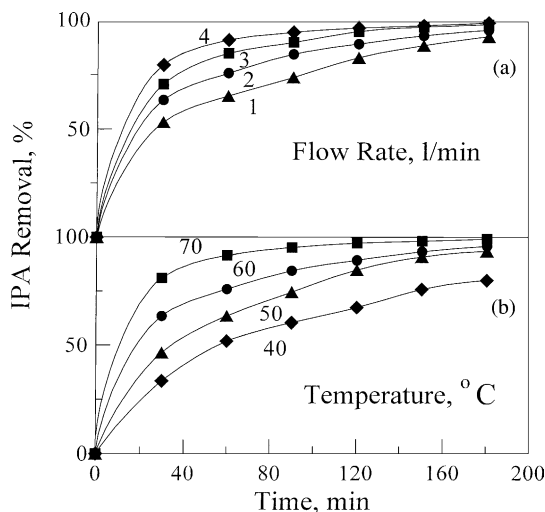
Fig. 1. IPA removal as a function of time for various air flow rates (a) and temperatures (b) with initial IPA concentration of 32,310 mg/l.

62,150 ± 16,750 mg/l, but its biodegradability, as represented by the BOD/COD ratio, was low at 0.124 ± 0.032, reflecting the existence of refractory organic compounds. The conductivity was also high at 3244 ± 312 μmh/cm which was attributable to the presence of salts. The initial IPA concentration was found to be 34,170 ± 15,200 mg/l. Such a high IPA concentration prompted the adoption of air stripping for IPA recovery.

3.2. IPA recovery by air stripping

The three important operating parameters to be ascertained in the air stripping tests were the air flow rate, temperature and stripping time. Fig. 1(a) shows the IPA removal, as determined from the changes of IPA concentration in the stripping column, as a function of stripping time for various air flow rates between 1 and 4 l/min. The figure reveals that the IPA removal increases rapidly within 1 and 1.5 h for all air flow rates, indicating a strong influence on the IPA removal during this period. The effect of air flow rate diminishes gradually as the stripping continued beyond that. After 3 h of air stripping, the IPA removal for all air flow rates is over 90% and varies within a small range of less than 10%. Considering the overall IPA stripping efficiency, energy consumption and operating complications of high air flow rate, an air flow rate of 1 l/min and a stripping time of 3 h would be deemed sufficient for the present IPA recovery purpose.

The temperature effect on the IPA stripping was demonstrated in Fig. 1(b). There was a significant spread of IPA removal for various temperatures before 1.5 h of air stripping. At 3 h of stripping, the IPA removal went up from 80.5 to 93% as the stripping temperature was increased from 40 to 50 °C. As the stripping temperature was further raised from 50 to 70 °C, the IPA removal was elevated from 93 to 99%, a much less significant improvement
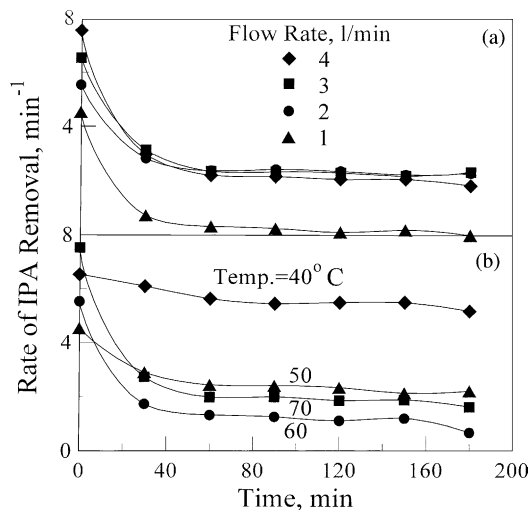
Fig. 2. Rate of IPA removal as a function of time for various air flow rates (a) and temperatures (b) with initial IPA concentration of 32,310 mg/l.

than the improvement between 40 and 50 °C. Hence from the viewpoint of energy saving, 50 °C or no more than 60 °C would be sufficient for the present stripping operation.

Pertaining to Fig. 1(a) and (b), the rates of IPA removal for various air flow rates and temperatures were demonstrated in Fig. 2(a) and (b). It is noted that the rate of IPA removal represents the slope of the IPA removal curve at a given time. Except for the case of 40 °C shown in Fig. 2(b), the rate of IPA removal is seen to decrease rapidly as the stripping time increases up to 60 min. After that, the rate of IPA removal appears to approach a constant value. In fact, such a rapid rate of IPA removal was also reflected by a rapid increase in the IPA removal shown in Fig. 1(a) and (b).

A side condenser was employed for IPA condensation from the gaseous mixture exiting the stripping column. It is noted that the gaseous mixture consisted of IPA, water vapor and air. Such a condensing system was found unable to completely remove of IPA and water vapor from the gaseous mixture. This is due primarily to the lowering of condensation temperature according to thermodynamic principle. For over 10 test runs using raw wastewaters with an initial IPA concentration between 18,750 and 42,580 mg/l, approximately 40–70% of IPA and some water were condensed out from the gaseous mixture in the side condenser and the rest left the condenser with air. A typical run, for example, started with 1 l of wastewater containing 32,310 mg/l IPA. Operating at 60 °C and with 1 l/min air flow rate, only 624.5 ml of wastewater containing 594 mg/l IPA remained in the stripping column after 3 h of stripping and a total of 154.5 ml condensate was collected that had an IPA concentration of 112,784 mg/l. Hence out of the original 31,780 mg of IPA in the raw wastewater, 53.9% was recovered in the condensate, 1.2% remained in the stripping column and the rest (44.9%) left the condenser in the gaseous mixture. Thermodynamic principles have dictated that complete recovery of IPA by such a simple condensation is difficult unless a cryogenic condensation is utilized. As an alternative, an adsorption system

using activated carbon or macroreticular resin can be employed to capture the IPA in the gaseous mixture exiting the condenser. Work is currently in progress with an attempt to improve the IPA recovery system. It is noted that the condensate collected using the present condensing system was found to contain only IPA and water and no other impurity. Hence, reuse of the recovered IPA solution is feasible.

3.3. Fenton oxidation

After air stripping for IPA recovery, the wastewater had a COD about 50,000 mg/l and was treated by Fenton oxidation that employs combined oxidants, hydrogen peroxide (H_2O_2) and ferrous sulfate (Fe_2SO_4). In the previous investigations on Fenton oxidation of various industrial wastewaters [6–9], the wastewater COD concentration was usually much lower than 5000 mg/l. The present semiconductor wastewater, even after IPA recovery, still had a high COD that could pose a significant challenge to Fenton oxidation. Preliminary test runs using a dosage of 5 g/l $FeSO_4$ and 1 ml/min feed rate of H_2O_2 (a total of 45 g/l H_2O_2) and operating at 70 °C yielded a COD reduction about 65%. The wastewater COD remained around 18,000 mg/l and this wastewater was still strongly colored. A much stronger dosage of Fenton reagents did not offer much help. Such a high effluent wastewater COD was beyond the capability of SBR treatment as a final polishing step. An acceptable initial COD level for SBR treatment is perhaps no more than 1000 mg/l [10–13]. To meet this requirement, it was decided that a lower COD wastewater from other parts of the same manufacturing plant was mixed with the high-strength semiconductor after air stripping. By doing so, the initial COD of the mixed wastewater would be more appropriate for Fenton oxidation. The low-strength wastewater from other parts of the manufacturing plant, that had ample supply, had a COD of 733 mg/l, ADMI of 693 and conductivity of 921 μmh/cm. Various mixing ratios of low- to high-strength wastewaters in the range of 1–5 were attempted. The effects of such a mixing ratio on the COD and ADMI removal of Fenton oxidation are displayed in Fig. 3(a) and (b). There is a drastic improvement in the COD removal as the mixing ratio is increased from 2 to 3. Hence, mixing of three volumes of low-strength wastewater to one volume of high-strength wastewater was appropriate, yielding an excellent 95% COD removal by Fenton oxidation. Similar results are also reflected in the ADMI reduction shown in Fig. 3(b). At the resulting ADMI level below 200, the effluent from Fenton oxidation had no visible difference from the tap water.

The previous investigations [6–9] had shown that the treatment efficiency of Fenton oxidation is highly pH dependent. Fig. 4 demonstrates such a pH dependence of COD removal. The treatment results are seen to be very good between pH 2 and 5. This observation is generally in line with those reported in the previous investigations.

The dosage of Fenton reagents is an important operating factor of Fenton oxidation also. Fig. 5 shows the effect of $FeSO_4$ dosage on the wastewater COD reductions for a fixed H_2O_2 flow rate of 1 ml/min. The largest improvement in the COD removal occurs below 5 g/l $FeSO_4$ in Fig. 5. Above that dosage level, the improvement becomes much less significantly. Hence a $FeSO_4$ dosage of 5 g/l is sufficient to achieve good treatment results. It is noted for these tests that at 1 ml/min feeding rate, the total H_2O_2 added to the Fenton reactor amounted to 45 g/l, leading to a $FeSO_4/H_2O_2$ ratio of 1/9. This dosage and $FeSO_4/H_2O_2$ ratio are significantly different from those reported in the previous investigations [6–9] and
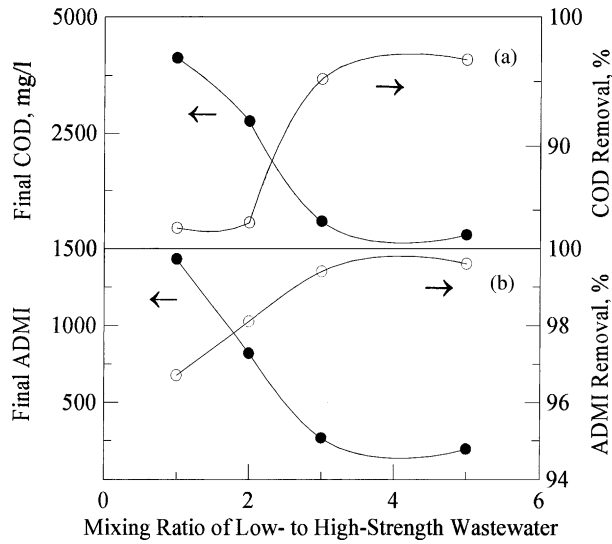
Fig. 3. COD (a) and ADMI (b) reductions of Fenton oxidation as a function of the mixing ratio of low- to high-strength wastewaters with 5 mg/l of $FeSO_4$, H_2O_2 feeding rate of 1 ml/min and 70 °C operating temperature.

the present Fenton reaction was apparently strong oxidation oriented. This is presumably due to significantly larger amount of organics in the present semiconductor wastewater that requires much strong oxidation to effect good decomposition.

By fixing the $FeSO_4$ dosage at 5 g/l, the influence of H_2O_2 feeding rate on the COD removal of Fenton oxidation is demonstrated in Fig. 6. The COD removal was drastically
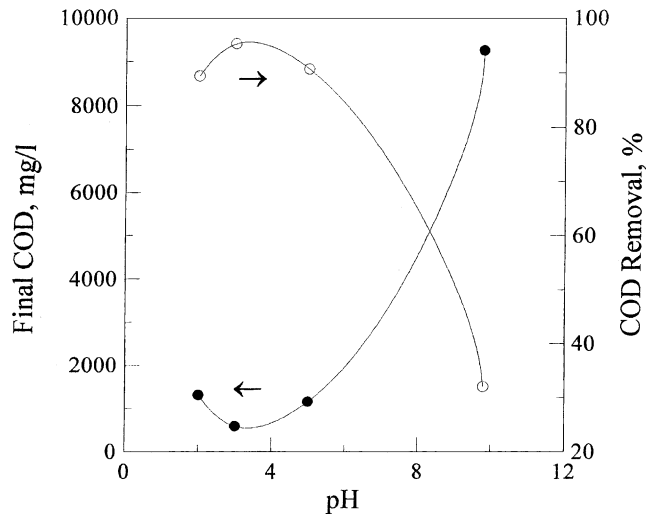

Fig. 4. COD and COD removal of Fenton oxidation as a function of pH with 12,360 mg/l of initial COD, 3/1 of mixing ratio of low- to high-strength wastewaters with 5 mg/l of $FeSO_4$, 1 ml/min of H_2O_2 feeding rate and 70 °C.
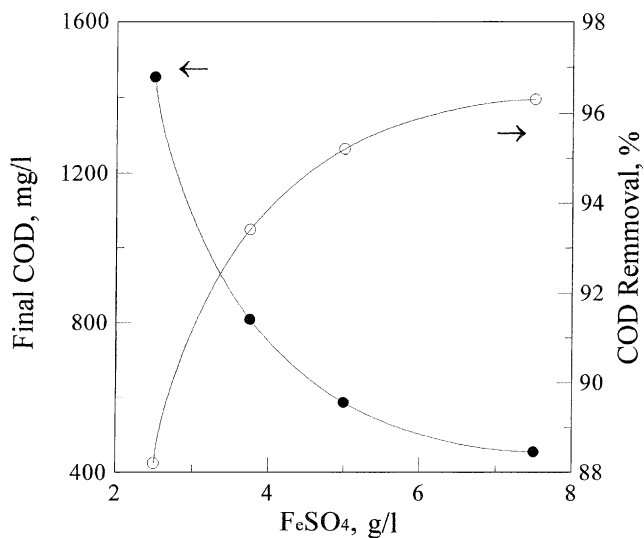
Fig. 5. COD and COD removal of Fenton oxidation as a function of the $FeSO_4$ dosage with 3/1 mixing ratio of low- to high-strength wastewaters and 1 ml/min of H_2O_2 feeding rate, 70 °C operating temperature.

elevated from 46% at 0.5 ml/min H_2O_2 feeding rate to 95% at 1 ml/min. The improvement then levels off after that H_2O_2 feeding rate. Hence 1 ml/min H_2O_2 feeding rate was considered as optimum because of rapidly diminishing return beyond that level. It is noted that regardless of the rate of H_2O_2 addition, the H_2O_2 decomposition in the wastewater is very rapid approximately with an exponential H_2O_2 decay as reported in many previous
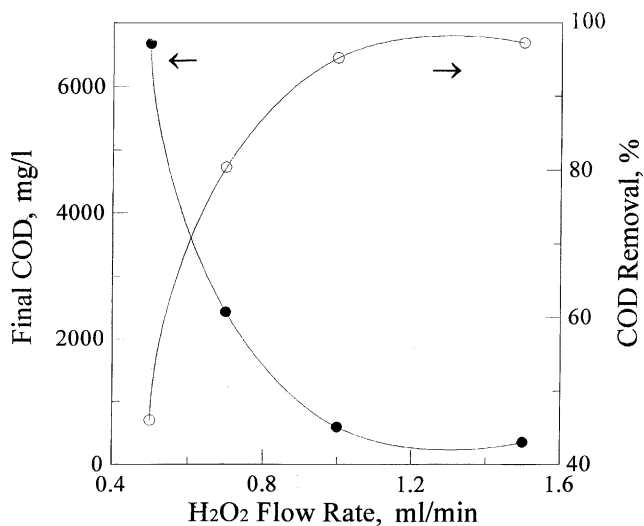

Fig. 6. COD and COD removal of Fenton oxidation as a function of H_2O_2 feeding rate with 3/1 mixing ratio of low- to high-strength wastewaters and 5 mg/l of $FeSO_4$.
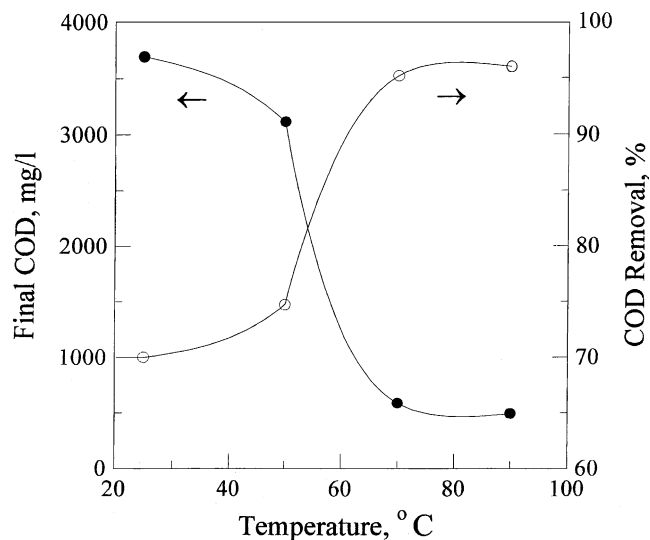
Fig. 7. COD and COD removal of Fenton oxidation as a function of temperature with 3/1 mixing ratio of low- to high-strength wastewater, 5 mg/l of $FeSO_4$ and 1 ml/min of H_2O_2 feeding rate.

investigations [6–9] and observed in the early tests of the present study. The Fenton oxidation corresponded approximately to this trend of H_2O_2 decay with a weak Fenton oxidation left at the latter stage of the treatment process. This fact prompted the present study to adopt a continuous feeding of H_2O_2. Such a continuous H_2O_2 feeding permits a relatively steady Fenton oxidation throughout the treatment period and improves the COD and ADMI removal of the wastewater.

It had been observed in the previous investigations [6–9] that an increase in operating temperature has a favorable effect on Fenton oxidation. This is due to that a higher temperature accelerates generation of hydroxyl radicals and thus the oxidation reaction. Fig. 7 shows the temperature effect on the Fenton COD reduction. Below 50 °C, the COD removal of Fenton oxidation stayed below 75% in this figure. However, as the temperature was raised above 70 °C, the COD removal was elevated to over 95%. A further increase in temperature had only limited benefit and is not considered.

The wastewater ADMI reduction by Fenton oxidation was not demonstrated in Figs. 4–7. In fact, under all operating conditions, the ADMI reduction by Fenton oxidation had been consistently excellent with a final ADMI of wastewater effluent under 500. With such a low ADMI, the wastewater effluent was very clear without any visible color.

3.4. SBR treatment

The effluent after the combined treatment by air stripping and Fenton oxidation had an average COD concentration of 610 ± 75 mg/l and a low ADMI below 15, as mentioned earlier. Except for the COD concentration, the effluent was very clear without a trace of color. To lower the COD to the discharge standard, the effluent was treated by the SBR

Table 1
SBR treatment efficiencies for different cycle times

Parameter	Run 1			Run 2			Run 3		
	Inlet	Outlet	Removal	Inlet	Outlet	Removal	Inlet	Outlet	Removal
pH	7.9	7.65		7.9	7.96		7.9	7.8	
Conductivity (μmh/cm)	4951	1962	60.7	4902	1814	62.5	4911	1744	64.4
COD (mg/l)	637	155	75.6	637	119	81.3	637	89	86
Cycle time (h)	6			8			12		
MLSS (mg/l)	3173			3395			3413		

method. In this treatment, the MLSS was maintained at 2800 ± 400 mg/l and the pH fell between 7 and 8.

Although 12-h cycle was illustrated in the experimental section, shorter cycle time was attempted in order to ascertain whether there is any room for shortening the operating cycle time of the SBR process. Table 1 compares the COD removal of the test runs for 6, 8 and 12-h SBR cycles. The table clearly reveals that the COD removal decreases steadily with a decrease in the SBR cycle time, reducing from 86% removal at 12-h cycle to 75.6% removal at 6-h cycle. For a direct discharge standard of less than 100 mg/l COD, only 12-h cycle meets this requirement. In fact, 12-h was also reported in several previous investigations [10–13] as a good cycle time for SBR process in terms of treatment efficiency and convenience of operation.

Based on the 12-h cycle, the SBR treatment was continued in the experimental tests for 15 cycles (7.5 days) to see if the high COD removal could be maintained. Fig. 8 displays
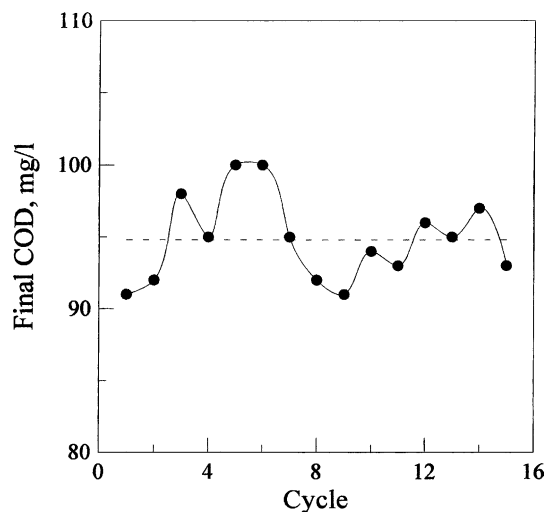

Fig. 8. Final COD concentration of the SBR effluent with 12-h cycle, influent COD of 585 ± 46 mg/l, MLSS of 2810 ± 320 mg/l.

the final effluent COD for these test runs. The effluent COD fluctuated slightly from cycle to cycle, but it remained consistently below 100 mg/l with an average of 94.8 mg/l for the 15 cycles. Therefore, as long as the operating parameters are properly maintained, good performance of the SBR treatment is expectable. The water quality of the final effluent from the SBR process was consistently excellent and the treated wastewater can in fact be recycled for non-potable uses. It is noted that the 7-cycle test adopted in the present work may not be able to completely reveal the long-term treatment stability of the SBR system. For practical purpose, a cyclic SBR test lasting about a month may be necessary.

4. Conclusions

Treatment of semiconductor wastewater was considered. This wastewater was characterized by a high IPA content over 35,000 mg/l, strong color and a high COD concentration up to 80,000 mg/l. These characteristics defy the traditional activated sludge treatment methods. In this study, air stripping, Fenton oxidation and SBR treatment were combined to deal with this high-strength wastewater. Based on the test results, the following conclusions can be drawn.

1. Air stripping using a packed column was found efficient in removing (IPA) from the wastewater. Operating at $70\,^{\circ}C$ and with 1 l/min air flow rate, over 95% IPA could be removed from the wastewater in 180 min. A simple side condenser operating at $5\,^{\circ}C$ cooling was capable of recovering only about 28% of IPA stripped out of the wastewater. For efficient and complete IPA recovery, more sophisticated recovery systems will be necessary. The recovered IPA solution had a high purity over 99% and can be recycled for reuse in the semiconductor manufacturing process.
2. The wastewater effluent after air stripping still had very high concentration over 50,000 mg/l which was beyond the treatment capacity of Fenton oxidation. Hence mixing of this high-strength wastewater effluent with low-strength wastewater from other sections of the semiconductor manufacturer in a ratio of 1–3 was necessary to facilitate Fenton oxidation. Treatment of the mixed wastewater was highly efficient over 95% COD and 99% ADMI (color) reductions. These results were achieved by operating Fenton oxidation at $70\,^{\circ}C$, with a dosage of 5 g/l $FeSO_4$ and 45 g/l H_2O_2 and 180 min of digestion. While $FeSO_4$ was added at the beginning of Fenton oxidation in a single shot, H_2O_2 must be fed continuously at a rate of 1 ml/min throughout the oxidation period for best treatment results.
3. Final SBR treatment of the wastewater effluent from Fenton oxidation entailed a MLSS about 3000 mg/l and 12-h cycle time. The SBR process was able to achieve a COD removal over 85%. The final wastewater COD amply meets the discharge standard of less than 100 mg/l. The overall water quality of treated wastewater was consistently very good and the wastewater could be considered for reuse.

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