Materials Research Express

**PAPER**

**Electro-fenton degradation of simulated petroleum wastewater by using Fe$_{78}$Si$_9$B$_{13}$ metallic glasses**

Xiao-Chen Xu$^1$$^,$, Zhong-Ling Shi$^1$ and Ke-Qiang Qiu$^1$

$^1$ School of Material Science and Engineering, Shenyang University of Technology, Shenyang 110870, People’s Republic of China
$^2$ Faculty of Mechanical and Power Engineering, Yingkou Institute of Technology, Yingkou 115014, People’s Republic of China

E-mail: kqqiu@sut.edu.cn

**Keywords:** Fe$_{78}$Si$_9$B$_{13}$ amorphous alloy, simulated petroleum wastewater, electro-Fenton method, chemical oxygen demand, O&G

**Abstract**

As the standard for the effluent from petroleum wastewater (PW) treatment become more and more strict, we adopt electro-Fenton (EF) oxidation method to degrade the simulated PW to surpass the limitations of conventional methods. The effects of initial pH value, current density, initial oil & grease (O&G) and initial chemical oxygen demand (COD) concentration on the degradation efficiency of the simulated PW were investigated on the premise of putting Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon as the anode and graphite plate as the cathode, respectively. The results show that under the optimal parameters, the COD and O&G removal rates can reach up to 89.6% and 93.8%, respectively. Compared to the traditional Fenton method, the EF method we used shows the advantages of reducing H$_2$O$_2$ consumption, power consumption, electrode mass loss and electrolysis time.

**Introduction**

In the refining production stage of the petroleum industry, a large amount of oil wastewater are being discharged into water environment [1–3]. Based on the complexity of the treatment process and the type of oil used in the refinery, the resulting wastewater composition is complex [4]. Physico-chemical and bioremediation methods for degrading these complex compounds are increasingly showing limitations, such as the partial degradation of organic components, the production of toxic intermediates, the large consumption of energy, and secondary pollution [5–7]. As one of advanced oxidation processes (AOPs), the Fenton method is widely used in high-concentration wastewater treatment because hydroxyl radicals (·OH) [8, 9] can be produced in such a process. However, the traditional Fenton method is limited due to the formation of iron sludge and the application of larger amount and high cost of H$_2$O$_2$ [10]. Therefore many methods related to Fenton process, such as electro-Fenton (EF) and photo Fenton, have been developed to reduce the usage of H$_2$O$_2$ and increase degradation efficiency. The photo Fenton-like process using Fe$_{78}$Si$_9$B$_{13}$ and Fe$_{73.5}$Si$_{13.5}$B$_9$Cu$_1$Nb$_3$ amorphous alloys can be effectively employed for BR3B-A dye degradation and mineralization [11]. Compared to photo method, many studies have shown that ·OH can be produced by electrocatalysis, which causes the reduction of the usage of H$_2$O$_2$ in Fenton process. Therefore the environment-friendly electrochemical advanced oxidation processes (EAOPs) based on EF process have received more and more attention in wastewater treatment [8, 12–15]. The results given by Wang et al [16, 17] have shown that the color and COD in the real dye wastewater can be effectively removed by in situ electrogenerated hydrogen peroxides based on EF method. Compared to traditional Fenton process, the EF process has demonstrated a dramatic improvement in dye degradation efficiency. These improvements along with other highly desirable properties inherent in the process, such as the low-cost, very stable and highly reusable Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon as the catalyst are the advantages of our research in the following statement. The reaction processes the prominent EF method are shown by the equations of (1)–(4).

\[
\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^-
\]

\[
\text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O}_2
\]
In addition, Fe$^{3+}$ produced in the equation can also be reduced to Fe$^{2+}$ on the cathode surface:

$$\text{Fe}^3+ + e^- \rightarrow \text{Fe}^{2+}$$  (4)

The glassy ribbon of Fe$_{78}$Si$_9$B$_{13}$, as a kind of amorphous alloy, can not only supply the Fe$^0$ that the Fentong reaction needed as shown in equation (1), but also does not have the defects that is generally existed in crystalline metals, such as grain boundaries, dislocations and segregation. The atoms are connected by metal bonds in short-range order and long-range disorder structure, characterized by the homogeneity of structure uniformity and ‘extreme defects’. The disorder state of atoms makes them possess a highly coordinated unsaturated state and a high catalytic activity which the crystalline alloy does not have [18]. In general, Fe-based amorphous alloys are inexpensive and have superior soft magnetic properties. At present, the application of Fe-based amorphous alloys is mainly focused on Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon, which has been widely used in electronic components and distribution transformers [19]. In order to broaden the application fields of the commercial Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon, many researches [20] on wastewater treatment have been done based on its superior catalytic performance. However, the oily wastewater treatment is rarely reported based on the EF process where the glassy alloys are employed as the electrodes. So in this paper, Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon was used as an anode and graphite plate as a cathode in the EF process to degrade the simulated petroleum wastewater, and the influence of various experimental parameters on the degradation efficiency of wastewater was discussed.

**Materials and methods**

**Chemical reagents and materials**

The NaOH and H$_2$SO$_4$ used to adjust the initial pH value of the solution were provided by Sinopharm Chemical Reagent Co., Ltd, China. Emulsifier OP-10 was supplied by Tianjin Damao Chemical Trade Co., Ltd Na$_2$SO$_4$ used as electrolyte was supplied by Sinopharm Chemical Reagent Co., Ltd, China. All the chemicals used in the study were of analytical reagent grade. Fe$_{78}$Si$_9$B$_{13}$ amorphous ribbon used as the anode was provided by Qingdao Yunlu Advanced Materials Technology Co., Ltd, China. Graphite plate used as the cathode was provided by Shenyang Jiayi Experimental Instrument Distribution Office, China.

**Simulation of petroleum wastewater**

The simulated petroleum wastewater (PW) is a mixture of emulsifier and oil. Diesel oil and emulsifier were selected to simulate the PW in this experiment. Therefore the simulated PW can be called simulated wastewater or oily wastewater in the following sections. The simulated PW is prepared by mixing water, diesel oil and emulsifier OP-10 in the ratios of 2000:5:2, 2000:15:6 and 500:5:2, respectively, in beakers stirred at a speed of 100 rad min$^{-1}$ and stored in dark when finished.

**Electro-Fenton experiments**

Firstly, the anodes with 60 mm long and 50 mm width were cut from the Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon coil with a width of 140 mm and a thickness of 24 ± 1 μm. The dimension of cathode made of graphite plate was 60 mm × 50 mm × 5 mm. The electrolysis device is consisted of breaker, electrodes, electric stirrer and direct current (DC) supply. The schematic diagram of the device is shown in figure 1. The current required in the experiments is provided by the XD1723A DC power supply produced by Beijing Baixiang Ruida Technology Co., Ltd, China.

The volume of the simulated wastewater in each group was 400 ml and the concentration of Na$_2$SO$_4$ electrolyte was 0.15 M. At same time the pH value of the wastewater was adjusted by using 1 mol H$_2$SO$_4$ and/or 1 mol NaOH [21] in according with requirement. In order to promote the rate of the initial reaction, a little H$_2$O$_2$ with dosage of 16.68 mM was added to each sample. The current density in our experiments was controlled under 10 A m$^{-2}$ by considering the energy and anode consumption as well as the results reported by the reference [22]. Our preliminary experiments have indicated that the degradation efficiency of the simulated wastewater was almost unchanged after 100 min treatment, so all experiment was ended in 100 min. The whole process consists of agitation, stillness and precipitation, then the solution supernatant was taken in time interval of about 20 min. The COD and O&G the simulated wastewater before and after treatment were determined by rapid airtight digestion and infrared spectrophotometry respectively. The specific experimental parameters of a single variable are shown in table 1.
Results and discussion

COD and O&G removal from the simulated wastewater by EF process

Effect of initial pH value

Figure 2 shows the effect of pH value on the COD removal rate from the simulated wastewater by EF process. Each curve is roughly in a mirror image of ‘S’ type, with the decrease of pH, COD removal rate shows an upward trend. The COD removal rate reaches up to 89.6% after 100 min reaction at pH 3.5 or pH 2.5 of the simulated wastewater. While the reaction time is lower than 100 min, the COD removal rate for the pH 2.5 of the simulated wastewater is a little higher than that of the pH 3.5. Generally, there is not much difference between the removal rate for the two pH values. However over 10% is decreased for the COD removal rate when further increase the pH value to 4.5 or 5.0. According to experimental results, the pH 3.5 was chosen as the optimal value by considering the corrosion and environmental aspect of highly acidic solution.

Based on the above results the effect of pH value on the COD removal rate can be analyzed. It can be seen from the reaction equation (2) that in order to produce $\text{H}_2\text{O}_2$ during the EF process, $\text{H}^+$ needs to be...
continuously consumed, but when the pH is too low, the produced H$_2$O$_2$ could be excessive and react with ·OH, as shown in the equation (5) [23]. The lower performance of HO$_2$ · leading to reduce the degradation, manifests itself as a slow increase in COD removal. When the pH is too high, OH$^-$ combines with metal ions in the solution to form hydroxide precipitates and inhibits the generation of ·OH, such reducing the COD removal rate of the simulated wastewater.

\[
\cdot \text{OH} + \text{H}_2\text{O}_2 \rightarrow \text{HO}_2 \cdot + \text{H}_2\text{O}
\]  

(5)

Figure 3 shows the effect of pH value on O&G removal rate from the simulated wastewater by EF process. The O&G removal rate is largely affected by the pH value. At pH value of 2.5 or 3.5, the O&G removal rate can reach about 95% after 100 min of electrolysis, while at pH value of 5, O&G removal rate can only reach 79%, which is corresponding to 60 min for the pH values of 2.5 or 3.5. Therefore, in the process of degradation of the simulated wastewater by EF method, with the decrease of pH, the time required for mineralization of pollutants in the wastewater is gradually shortened, and the maximum degradation rate is obtained at pH values of 2.5 or 3.5. Therefore, the optimal pH value chosen is 3.5, which combines the two monitoring indicators of COD and O&G removal rates of the simulated wastewater.

In acidic conditions, it is advantageous to the generation of H$_2$O$_2$, which further improves the probability of H$_2$O$_2$ adsorbing to amorphous surface to catalyze the generation of ·OH, and OH$^-$ will be produced during the oxidation process, as shown in the equations (6) and (7). When H$^+$ is sufficient, it is advantageous to promote the positive reaction.

\[
\text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O}_2
\]  

(6)

\[
\text{H}_2\text{O}_2 + \text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + \cdot \text{OH} + \text{OH}^- 
\]  

(7)

**Effect of current density**

Figure 4 shows the effect of current density on COD removal rate from the simulated wastewater by EF process. The electric current applied during the EF process is the motive force of O$_2$ reduction. Eventually H$_2$O$_2$ is generated at the cathode. As the current increases, the amount of H$_2$O$_2$ also increases, thereby more ·OH radicals were produced in the electrolyte [24]. As shown by the equations (8) and (9), at high voltage, oxygen on the anode and hydrogen on the cathode discharge, leading to a reduction in the main reaction rate [25]. It is not difficult to see from figure 4 that when the current density is increased to 10 mA cm$^{-2}$, the increase of the COD removal rate becomes limited. Considering the degradation efficiency and cost comprehensively, the optimal degradation effect is obtained when the current density is 6.5 mA cm$^{-2}$.

\[
2\text{H}_2\text{O} \rightarrow 4\text{H}^+ + \text{O}_2 + 4e^-
\]  

(8)

\[
2\text{H}^+ + 2e^- \rightarrow \text{H}_2
\]  

(9)

Figure 5 shows the effect of current density on O&G removal rate from the simulated wastewater by EF process. At the beginning, in order to promote the start of the reaction and reduce the degradation time, although a little H$_2$O$_2$ was added before the reaction, the O&G removal rate is relatively low due to the low concentration of ·OH in the first 20 min. At the middle stage, with the increase of hydrogen peroxide...
concentration as time pass by, the degradation rate reaches maximum. At the last stage, the residual oil content is low, and the probability of collision with ·OH is also reduced, and the degradation rate tends to be flat. Overall, the O&G removal rate is greatly affected by current density. In the process of the current density was increased from 3.2 mA cm\(^{-2}\) to 6.5 mA cm\(^{-2}\), the O&G removal rate increases from 60% to 92% until the maximum degradation effect is reached. Combining the removal rates of COD and O&G, the current density is 6.5 mA cm\(^{-2}\) as the optimized parameter in the degradation of the simulated wastewater by EF process.

Effect of initial COD

Figure 6 shows the effect of initial COD on COD removal rate from the simulated wastewater by EF process. The results show that the lower the initial COD concentration, the higher the COD removal rate within the first 20 min, after which the COD removal rate begins to increase more rapidly for the wastewater with initial COD concentration of 683 mg l\(^{-1}\) than that of two other wastewater with smaller or larger COD concentration of 469 and 900 mg l\(^{-1}\), respectively. When the processing time is over 70 min, the initial COD of the wastewater with the best COD removal rate among the three initial COD concentrations is the one with the middle value of 683 mg l\(^{-1}\) which corresponds to the optimal COD removal rate of 89.6% after 100 min reaction.

Effect of initial O&G

Figure 7 shows the effect of the initial O&G on O&G removal rate from the simulated wastewater by EF process. We can find that the degradation rate is roughly proportional to the initial O&G at the first 20 min. The lower the
initial oil concentration, the lower the oil concentration in the wastewater after reaction. This is because that the amount of ·OH generated in the reaction is comparable, and the probability of oxidation of organics adsorbed to the electrode is approximately the same, thereby, positive reaction rate is promoted \([26]\). However, after 20 min reaction, the increase of the O\&G removal rate for the simulated wastewater with different initial O\&G is quite different. It is obvious that the simulated wastewater with initial O\&G lower than 19.82 mg L\(^{-1}\), the O\&G removal rate increases more rapidly than the one with initial O\&G of 22.04 mg/L. Therefore, if the initial oil concentration is very high, in order to meet the discharge standard under the same conditions, the wastewater should be diluted first and then treated.

From above experiments, we can conclude the optimal parameters of the COD and O\&G removal rate from the simulated wastewater during EF process by using Fe\(_{78}\)Si\(_9\)B\(_{13}\) glassy ribbon as the anode, which is shown in Table 2. It can be observed that the COD and the O\&G removal rates reach 89.6\% and 93.8\%, respectively.

### Table 2. Optimal conditions found by experimental verification in treatment of the simulated wastewater by using Fe\(_{78}\)Si\(_9\)B\(_{13}\) glassy ribbon during EF process.

| H\(_2\)O\(_2\) dosage | pH  | Current density | Initial COD   | Time    | Initial O\&G | O\&G degradation | COD removal |
|----------------------|-----|----------------|---------------|---------|--------------|------------------|-------------|
| 16.68 mM             | 3.5 | 16 mA cm\(^{-2}\) | 683 mg L\(^{-1}\) | 100 min | 19.82 mg/L   | 93.8\%           | 89.6\%      |

![Figure 6. Effect of initial COD on COD removal rate by EF process.](image1)

![Figure 7. Effect of initial O\&G on O\&G removal rate by EF process.](image2)
Besides, we observed that the used Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon is very easily to retrieve and friendly to the environment.

**Stability and recycling utilization of Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon in EF process**

In order to investigate the influence of EF process on the phase stability of Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon, the XRD patterns of the ribbons before and after use are shown in figure 8. The XRD patterns display the typical profile of amorphous alloy with no detectable sharp Bragg peaks overlaid on the main peak, which indicates the glassy nature of the ribbon. It should be noticed that some peaks corresponding to iron oxides are often observed for the 2\(\theta\) in the range of 30–35 degree in the XRD pattern for the used ribbon due to electrolytic corrosion effect.

Figure 9 shows of the simulated wastewater measured during the repeated use of the glassy ribbon. It is clear that even if the removal rate of COD decreases gradually after the ribbon recycling use, the ribbon still maintains a high catalytic activity after 4 cycle experiments, and therefore the COD removal rate remains at a high level as well.

In order to clarity the surface morphology of glassy ribbon after cycle use on the degradation efficiency of simulated wastewater, figures 10(a) and (b) show the typical SEM images of glassy ribbons after one and four
cycling use, respectively. Many weak corrosion pits were observed on the overall relatively flat surface of the ribbon used for one time, as shown in figure 10 (a). The pits on the surface of the ribbon are able to increase the collision area between the organic molecules and the ·OH, and then promote the degradation reaction. As a relatively active component, the iron in the amorphous alloy will be eroded under acidic conditions to form Fe$^{2+}$. The action of Fe$^{2+}$ and H$_2$O$_2$ causes the decomposition of H$_2$O$_2$ to produce a large amount of ·OH, and the ·OH promotes the degradation reaction. At the same time as a special zero-valence metal alloy, Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon contains three elements, i.e., iron, silicon, and boron. Iron and silicon can be regarded as two electrodes to form a primary battery, which can accelerate the decomposition of organic matter during EF process. Therefore, in the case of electrolysis, both the degradation reaction speed and degradation effect can be improved. Figure 10(b) shows the surface morphology of the amorphous ribbon after 4 cycles of the experiment. It can be seen that the corrosion area becomes larger and the corrosion degree becomes deep. Therefore there are lot of corrosion products on the surface, which is an important reason for the reduction of degradation efficiency with the increase of the cycle numbers.

**Comparison of Fe-based amorphous alloy electrode with Fe crystalline electrode**

Figure 11 shows the comparison between the Fe$_{78}$Si$_9$B$_{13}$ amorphous ribbon and Fe crystalline electrode at different current density. In this experiment, the loss of electric energy, $E_{O&G}$, and electrode quality required to degrade oil content per milligram, $m_{O&G}$, were used to represent the consumption of electric energy and electrode. The $E_{O&G}$ and $m_{O&G}$ is expressed by equations (10) and (11), respectively. Where U is the voltage, i is the current, t is the time that voltage applied, V is the volume of experimental wastewater, $C_0$ is the initial O&G, $\lambda$ is the degradation efficiency, $m_0$ is the mass of amorphous anode before reaction, and $m$ is the mass of amorphous anode after reaction.

$$E_{O&G} = \frac{U \times I \times t}{V \times C_0 \times \lambda}$$ (10)

$$m_{O&G} = \frac{m_0 - m}{V \times C_0 \times \lambda}$$ (11)

It is not difficult to see that the oil removal rate of the simulated wastewater by using Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon as the anode is higher than that of Fe crystalline electrode at all current densities, at same time the power consumption and electrode loss are also lower than those of Fe crystalline electrode. The reason for this is that the anodes made of Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon possess the higher activity and higher corrosion resistance than the crystalline Fe anodes. In the EF process, generally, the removal of O&G in the simulated wastewater is mainly through oxidation by Fenton and flocculation by electrolysis. The dissolution rate of anodic iron resulted from the formation of Fe(OH)$_3$, the flocculant, is faster for the Fe crystalline anodes with lower corrosion resistance. So the mass loss of Fe crystalline electrodes is large than that of Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon expect that the glassy ribbon electrode can also play a catalytic role. In order to achieve the same degradation effect as the glassy ribbon, the electrolysis time of Fe crystalline electrodes should be prolonged accordingly. Now we can conclude that

![Figure 10. SEM images of Fe$_{78}$Si$_9$B$_{13}$ glassy ribbon after the first cycle (a) and four cycles (b) of use.](image-url)
Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon is able to degrade oily wastewater effectively in the case of less power consumption, less electrode mass loss and shorter electrolysis time.

To date, many researchers have used the EF process with different electrodes to treat various large-capacity wastewater. As shown in table 3, comparisons between the results of the studies show that the EF process shows outstanding prominence in the treatment of oily wastewater.

Conclusions

In the process of degradation of the simulated PW by EF process where the Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon as the anode and the graphite plate as the cathode, the effects of processing parameters, such as pH value, current density, initial COD concentration and the type of the anodes used in the EF process, on the degradation efficiency were studied respectively, and the following conclusions were obtained:

(1) The optimal processing parameters are included the pH value of 3.5, the current density of 16 mA cm\textsuperscript{-2} and initial COD concentration of 683 mg L\textsuperscript{-1} (or initial O&G concentration of 19.82 mg L\textsuperscript{-1}). Under the optimal parameters, the COD and O&G removal rates can reach up to 89.6% and 93.8%, respectively, within 100 min of treatment.

(2) Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon possesses a good structural stability and excellent surface activity. The amorphous nature of the glassy ribbon is unchanged and the degradation efficiency is not obviously reduced after it being cycled for 4 times.
### Table 3. Comparison between the removal efficiency in wastewater treatment by EF process.

| Pollutants | Electrodes | Conditions | Removal rate (%) | References |
|------------|------------|------------|------------------|------------|
| Dye        | graphite- Pt/Ti | [Na₂SO₄] = 0.1 M, pH = 3, current density = 68 A/m², Aeration rate = 0.3 L min⁻¹ | 70.6       | [14]       |
| Acid red   | RuO₂/Ti- ACF  | pH = 3, [Na₂SO₄] = 0.05 M, current = 0.05 A | 73.3       | [15]       |
| Petrochemical | Stainless steel-Stainless steel | pH = 3, current = 0.6 A | 50         | [16]       |
| Dye        | Pt-PAN based active carbon fiber | pH = 3, current density = 3.2 mA cm⁻², Aeration rate = 150 cm³/min | 75.2       | [17]       |
| oily       | graphite-Fe₂Si₆B₁₁ amorphous alloy | pH = 3.5, [Na₂SO₄] = 0.15 M, current density = 6.5 A m⁻² | 89.6       | This work  |
(3) Compared with the traditional Fenton method, the H\textsubscript{2}O\textsubscript{2} consumption is reduced in the EF process. While compared to crystalline Fe anode, the Fe\textsubscript{78}Si\textsubscript{9}B\textsubscript{13} glassy ribbon is able to degrade oily wastewater effectively in the case of less power consumption, less electrode mass loss and shorter electrolysis time.

Acknowledgments

This work was supported by the Education Department of Liaoning Province (Grant No. 201724123). Natural Science Foundation of Liaoning Province (Grant No. 2019ZD0373).

ORCID iDs

Xiao-Chen Xu © https://orcid.org/0000-0002-1212-6386

References

[1] Jorge V F I C et al 2012 Removal of effluent from petrochemical wastewater by adsorption using organoclay Petrochemicals 14 277–94
[2] Long Y, Hong Z M et al 2013 Electrochemical treatment of petroleum refinery wastewater with three-dimensional multi-phase electrode Desalination 276 397–402
[3] Jéssica H B R et al 2012 Application of electrochemical oxidation as alternative treatment of produced water generated by Brazilian petrochemical industry Fuel Process. Technol. 96 80–7
[4] Alessandra C, Antonio V C et al 2006 Treatment of petroleum refinery sourwater by advanced oxidation processes J. Hazard. Mater. 137 178–84
[5] André J C S et al 2013 Electrochemical treatment of fresh, brine and saline produced water generated by petrochemical industry using Ti/IrO\textsubscript{2}–Ta\textsubscript{2}O\textsubscript{5} and BDD in flow reactor Chem. Eng. J. 233 47–55
[6] Davarnejad R et al 2014 Petrochemical wastewater treatment by electro-Fenton process using aluminum and iron electrodes: statistical comparison Journal of Water Process Engineering 3 18–24
[7] Fu F L, Wang Q and Tang B 2010 Effective degradation of C.I. Acid Red 73 by advanced Fenton process J. Hazard. Mater. 174 17–22
[8] Nidhesh PV and Gandhimathi R 2012 Trends in electro-Fenton process for water and wastewater treatment: an overview Desalination 299 1–15
[9] Brillas E, Sirés I and Oturan M A 2009 Electro-Fenton process and related electrochemical technologies based on Fenton’s reaction chemistry Chem. Rev. 109 65–70
[10] Hyunhee L and Makoto S 2008 Removal of COD and color from livestock wastewater by the Fenton method J. Hazard. Mater. 153 1314–9
[11] Jia Z, Zhang W C, Wang W M, Habibi D and Zhang L C 2016 Amorphous Fe78Si9B13 alloy: an efficient and reusable photo-enhanced Fenton-like catalyst in degradation of cibacron brilliant red 3B-A dye under UV-vis light Applied Catalysis B: Environmental 192 46–56
[12] Mohanty N R and Wei I W 1993 Oxidation of 2,4-dinitrotoluene using Fenton’s reagent: reaction mechanisms and their practical applications Hazard. Waste Hazard. Mater. 10 171–83
[13] Elena G et al 2008 Mineralization of salicylic acid in acidic aqueous medium by electrochemical advanced oxidation processes using platinum and boron-doped diamond as anode and cathodically generated hydrogen peroxide Water Res. 42 699–511
[14] Wang A M, Qu J H and Liu H J 2005 Mineralization of an azo dye Acid Red 14 by electro-Fenton’s reagent using an activated carbon fiber cathode Dyes Pigments. 65 227–33
[15] Ting W P, Huang Y H and Lu M C 2007 Catalytic treatment of petrochemical wastewater by electro-assisted Fenton technologies React. Kinet. Catal. Lett. 92 41–8
[16] Wang C T, Hu J L, Chou W L and Kuo Y M 2008 Removal of color from real dyeing wastewater by electro-Fenton technology using a three-dimensional graphite cathode J. Hazard. Mater. 152 601–6
[17] Wang C T, Chou W L, Chung M H and Kuo Y M 2010 COD removal from real dyeing wastewater by electro-Fenton technology using an activated carbon fiber cathode Desalination 253 129–34
[18] Yang J P 2014 Application of Fe-based amorphous and its composites in organic wastewater treatment Master Thesis Shandong University
[19] Wang P 2012 Application of Fe-based amorphous in phenolic wastewater treatment Master Thesis Shandong University
[20] Zhang L C, Jia Z et al 2019 A review of catalytic performance of metallic glasses in wastewater treatment: recent progress and prospects Prog. Mater Sci. 105 1–42
[21] Wang N et al 2015 A review on Fenton-like processes for organic wastewater treatment J. Environ. Chem. Eng. 4 762–87
[22] Zhang F, Li G M and Zhao X H 2004 Study status and progress in wastewater treatment by electro-Fenton method Ind. Water Treat 24 9–13
[23] Salem M A et al 2009 Kinetics of degradation of allura red ponceau 4R and carmosine dyes with potassium ferrioxalate complex in the presence of H\textsubscript{2}O\textsubscript{2} Chemosphere 76 88–93
[24] Narayanan T S N et al 2003 Degradation of Ochlophenol from aqueous solution by electro-Fenton process Fresenius Environ. Bull. 12 776–80
[25] Zhang H, Fei C, Zhang D and Tang F 2007 Degradation of 4-nitrophenol in aqueous medium by electro-Fenton method J. Hazard. Mater. 145 227–32
[26] Hu C Y et al 2006 Kinetics study of leachate treatment by electro-Fenton process in domestic waste incineration plant Environment Science 27 1591–5