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RESEARCH

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Acetic acid mediated leaching of metals from lead-free solders

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Abstract

Background: The replacement of lead (Pb)-bearing solders by several Pb-free solders is a subject of intense research in these days due to the toxic effects of Pb on the environment. However, the Pb-free solders contain metals such as silver (Ag), copper (Cu), and zinc (Zn). The increasing use of these Pb-free solders again increases the risk of release of Ag, Cu, and Zn metals into the environment. The Pb-free solders can, therefore, be used as a secondary source for the metals which will not only help in environmental protection but also for the resource recovery.

Results: This study reports a process to leach metals from hazardous soldering materials by acetic acid. Acetic acid was found more effective for metal recovery from the tin–copper (Sn–Cu) solder than tin–copper–silver (Sn–Cu–Ag) solder. Various process parameters were optimized for recovery of metals from Sn–Cu solder. It required 30 h for 100% recovery of Cu and Sn, respectively. The metal recovery increased gradually with an increase in acid concentration approaching complete recovery at an acid concentration of 80%. Effect of shaking speed and temperature on the recovery of metals from Sn–Cu solder was studied. The metal recovery decreased with an increase in solder weight.

Conclusion: The present study reveals an effective process to recycle the Pb-free solders. The low concentration of acetic acid was also found significant for metal leaching from solder. The research provides basic knowledge for recovery of metals from Pb-free solders.

Keywords: Industrial waste, Solders, Metal recovery, Acetic acid

Background

The tin–lead (Sn/Pb) solders are widely used in electronic equipment. However, lead is known to be a toxic material. It has health and environmental concern (Yoo et al. 2016). Therefore, there is an increasing demand in replacing Sn/Pb solders with Pb-free solders in the electronics industry (Cheng et al. 2011). Nowadays, more progress has been achieved in developing Pb-free solders. The tin–silver (Sn–Ag), tin–zinc (Sn–Zn), and tin–copper (Sn–Cu) solder alloys are replacing Pb-bearing solders (Abtew and Selvaduray 2000; Zeng and Tu 2002; Wu et al. 2004; Gao et al. 2012; Yang et al. 2016). The replacement of Pb-bearing solders by several Pb-free solders can avoid potential environmental risk from toxic Pb elements. However, excessive use of Pb-free solders releases metals, such as Ag, Cu, and Zn, into the environment. This would again pose a risk to ecosystems and human health (Cheng et al. 2011; Lim and Schoenung 2010). It is therefore essential to recover the metal values from the newly developed lead-free solders.

Several methods have been proposed to treat lead-free solders to recover their valuable metals. The existing processes for recycling spent solders include pyrometallurgy (Lee et al. 2007), hydrometallurgy (Yoo et al. 2012), and biohydrometallurgy (Hocheng et al. 2014). For pyrometallurgical processes, high energy consumption is unavoidable. Also, it emits toxic gases. The biohydrometallurgical processes have been gradually replacing the hydrometallurgical ones due to their higher efficiency, lower costs, and fewer industrial requirements (Li et al. 2010; Hocheng et al. 2014). But the treatment period for biohydrometallurgical process is long. Hydrometallurgy is a well-established process for the separation and recovery of metal from industrial wastes. Using hydrometallurgical

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processes, a complete recovery of metals with high purity is possible. It requires low energy (Huang et al. 2009). The leaching of solders has been investigated using sodium hydroxide and sodium persulfate (Rhee et al. 1994), organic solvents (Takahashi et al. 2009), and nitric acid (HNO_3) (Yoo et al. 2012) as leaching agents. Notably, organic solvents are harmful to the environment (Yoo et al. 2012). The strong acid leachates release toxic gases like Cl_2, SO_3, and NO_x (Li et al. 2010, 2013). Also, the waste acid solution generated during the process is harmful to the environment. For the sustainable management of natural resources and to reduce environmental pollution, it is important to develop a simple recycling process to recover as much of the valuable metals as possible (Li et al. 2010, 2013; Shu et al. 2004). Organic acids could be an attractive extracting agent. With organic acids, the extraction can be performed at mildly acidic conditions (pH 3–5). A study reported the percolation leaching of the Cuban nickel tailings. The authors used tartaric acid and a mixture of tartaric and oxalic acids at different concentrations (Hernandez et al. 2007). Several studies reported the leaching of cobalt (Co) and lithium (Li) from spent lithium-ion batteries using various organic acids and hydrogen peroxide (Li et al. 2010, 2013). Merdoud et al. (2016) and Cameselle and Pena (2016) used organic acids as facilitating agents for electrokinetic decontamination of soils. Biswas and Mulaba-Bafubiandi (2016) used citric, oxalic, and gluconic acids for the leaching of copper (Cu) and cobalt (Co) from oxidized ore. They achieved maximum recovery of Cu and Co at 80 °C using 150 mM of citric acid. Their findings also suggest that the recovery of Cu and Co from the oxidized ore was highly dependent on the amenability of the ore mineral to organic acid attack. Suanon et al. (2016) used organic acid to improve the removal of metals from the soil because of its ready availability, relatively inexpensiveness, and environmentally benign nature. Also, the organic acids are biologically degradable (Veeken and Hamelers 1999). Considering these advantages of organic acids for metal leaching, the acetic acid was introduced as a leaching reagent in the present study. Acetic acid is commonly known as moderate and weak chelating agents (low molecular weight organic acid). It has been extensively used in the food industry, the medical field, and the manufacturing industry, among others. The present study was carried out to determine the effectiveness of acetic acid for recovery of metals from solders, and also, to determine various factors influencing metal dissolution from solder. Further, the results were compared with the biologically produced acetic acid using *Acetobacter* sp.

Methods

Materials

The solders Sn–Cu (63–37%) and Sn–Cu–Ag (60–37–3%) were supplied by Taiwan-Solid Enterprises Limited. For the experiments, the Sn–Cu and Sn–Cu–Ag solders were cut into 3 mm size. All the chemicals were purchased from Sigma Aldrich.

Microorganism and culture conditions

Acetobacter sp. TISTR 102 was obtained from BCRC strain collection, Taiwan, R.O.C. The strains were cultured in Yeast Glucose ethanol acetic acid (YGEA) medium for acetic acid production and the acid production rate was estimated by titration method as described by Beheshti Maal and Shafiei (2010). Briefly, 5 ml of culture was mixed with 20 ml of distilled water and mixed with 5 drops of phenolphthalein indicator. The solution was titrated against 0.5 N NaOH. The amount of acetic acid (g) produced in 100 ml medium was calculated as follows:

$$\text{Acetic acid (g/100 ml)} = \text{Volume of NaOH (ml) used in titration} \times 0.03 \times 20.$$

Leaching of solder pieces by acetic acid

For leaching experiments, two types of lead-free solders were used viz., Sn–Cu and Sn–Cu–Ag. All samples were rinsed with distilled water, 75% ethanol, and dried before use. Acetic acid (100%) was used as a leaching agent. The leaching experiments were carried out according to Joksic et al. (2005) and Granata et al. (2011) with some modifications.

The effect of acetic acid volume on the solder leaching efficiency

In an initial experiment, the 100 mg of Sn–Cu and Sn–Cu–Ag solders were incubated with 10 ml acetic acid (100%) separately in 25 ml conical flask at 30 °C for 24 h. The flask was covered to avoid evaporation of acid. The aliquots of liquid samples were taken after 24 h, filtered, and analyzed for metal content by inductively coupled plasma resonance spectroscopy (ICP/OES).

The effect of incubation time on the solder leaching efficiency

The effect of incubation time on metal leaching from Sn–Cu solder was studied. The Sn–Cu solder pieces (100 mg) were covered with 10 ml of acetic acid (100%) in a 25 ml conical flask at 30 °C for 30 h. Over the course of the leaching process, the samples were taken at 10, 20, and 30 h and analyzed for metal content by ICP/OES.

The effect of various concentrations of acetic acid on the solder leaching efficiency

The effect of various concentrations of acetic acid on leaching of metals from Sn–Cu solder was studied. To study this parameter, two sets of experiments were carried out. In one set, the Sn–Cu solder pieces (100 mg) were covered with 10 ml of acetic acid (10–100%) in 25 ml conical flasks separately. In another set, the Sn–Cu solder pieces were covered with 10 ml of acetic acid (2–8%) in 25 ml conical flasks separately. These flasks were incubated at 150 rpm at 30 °C for 30 h.

The effect of acetic acid volume on the solder leaching efficiency

The Sn–Cu solder pieces (100 mg) were covered with variable volume (2–10 ml) of acetic acid (80%) in 25 ml conical flasks separately, to study the effect of volume of acetic acid on metal leaching. These flasks were incubated at 150 rpm at 30 °C for 30 h.

The effect of shaking speed on the solder leaching efficiency

Effect of variable shaking speeds on metal leaching from Sn–Cu solder was studied. The Sn–Cu solder pieces (100 mg) were covered with 4 ml of acetic acid (80%) in 25 ml conical flasks separately. These flasks were incubated at 0, 50, 100, 150, and 200 rpm at 30 °C for 30 h.

The effect of temperature on the solder leaching efficiency

Temperature optimum for metal recovery from Sn–Cu solder pieces (100 mg) was quantified. The solder pieces were covered with 4 ml of acetic acid (80%) in 25 ml conical flasks separately and incubated at various temperatures (30–50 °C) and 150 rpm for 30 h.

The effect of particle size on the solder leaching efficiency

Different sizes of Sn–Cu solder pieces (3, 5, and 7 mm) were covered with 4 ml acetic acid (80%) separately. These flasks were incubated at 150 rpm at 30 °C for 30 h.

The effect of solid–liquid ratio on the solder leaching efficiency

Variable weights (100–900 mg) of Sn–Cu solder pieces were covered with 4 ml acetic acid (80%) separately. These flasks were incubated at 150 rpm at 30 °C for 30 h.

The effect of biologically produced acetic acid on the solder leaching efficiency

The 3 mm Sn–Cu solder pieces (100 mg) were covered with 4 ml *Acetobacter* culture (grown at 30 °C at 150 rpm for 24 h) and incubated at 150 rpm at 30 °C for 30 h.

After exposure to the leaching solution, the samples were analyzed for metal content by ICP/OES for all the experiments. All the experiments were carried out in three sets.

Scanning electron microscope (SEM) analysis

The solder surface before and after treatment with acetic acid was analyzed by scanning electron microscope (SEM, JSM-5610 LV). The accelerating voltage used was 0.5–30 kV at a resolution of 10 μm (10 kV WD 11 mm).

Results and discussion

The basic experimental results for the metal leaching from Sn–Cu and Sn–Cu–Ag solders by acetic acid

In the present study, two types of solders Sn–Cu and Sn–Cu–Ag were used. Acetic acid was used as a leaching solution. The solders were incubated with acetic acid for 24 h. Table 1 shows an effect of acetic acid on metal leaching from Sn–Cu and Sn–Cu–Ag solders. It was observed that 38 (± 0.22), 37 (± 0.09), and 40 (± 1.00) % metal leaching was obtained for Cu, Ag, and Sn, respectively, from Sn–Cu–Ag solder in 24 h at 100:10 (mg/ml) solid-to-liquid ratio. The reaction of Sn–Cu solder with acetic acid showed more metal leaching. A 54 (± 0.15) and 61 (± 0.95) % metal leaching was obtained for Cu and Sn, respectively, from Sn–Cu solder in 24 h at 100:10 (mg/ml) solid-to-liquid ratio. These results are in contrast to Hocheng et al. (2014). They observed more metal leaching for Sn–Cu–Ag solder as compared to Sn–Cu solder by *A. niger* culture supernatant. This discrepancy occurred due to the organic acid used for leaching of metals. The *A. niger* culture supernatant used by Hocheng et al. (2014) contained citric acid. The present study used acetic acid as a leaching agent for leaching of metals from solders. The ability of organic acids to coordinate with metal ions decides the amount of metals leached. Thus, the formation of more stable ligand makes the metal leaching much easier (Gao et al. 2002). A number of studies have verified that the organic acid with more carboxyl groups is beneficial to the heavy metal leaching since the formed ligand is more stable. Therefore, the leaching ability of citric acid with 3 carboxyl groups is supposed to be higher than that of other organic acids having 2 carboxyl groups. The acetic acid

Table 1 Metal removal from Sn–Cu–Ag (100 mg) and Sn–Cu (100 mg) solder by 10 ml acetic acid (100%) in 24 h at 150 rpm and 30 °C

Sr. no.	Solder type	Metal extraction (%)		
		Cu	Ag	Sn
1	Sn–Cu–Ag	38.10 (± 0.22)	37.90 (± 0.09)	40 (± 1.00)
2	Sn–Cu	54.00 (± 0.15)	–	61.20 (± 0.95)

with only one carboxyl group possesses the lowest leaching ability (Gao et al. 2002; Qin et al. 2004; Schwab et al. 2008). However, the present study showed that the acetic acid possessed the remarkable leaching ability for Sn–Cu solder. It was presumed that the acid strength used for leaching experiments and the chemical bonding of Sn and Cu might have caused the entirely different results. Since more metal leaching was achieved for Sn–Cu solder, it was used for optimization of various process parameters in further experiments.

Effect of time on the efficiency of solder leaching by acetic acid

Figure 1 illustrates an effect of leaching time on the metal leaching from the Sn–Cu solder. The metal leaching increased with an increase in incubation time. In 20 h, 49 (± 0.58) and 54 (± 0.26) % metal leaching was observed for Cu and Sn, respectively. The 100% metal leaching was observed for Cu and Sn, respectively, with further 30 h incubation of Sn–Cu solder with acetic acid. These results are advantageous as compared to Hocheng et al. (2014) since they required 96 h for complete metal leaching from Sn–Cu solder by *A. niger* culture supernatant.

Effect of acetic acid concentration on solder leaching efficiency

Two separate set of experiments were conducted to study an effect of acid concentration on the metal leaching from Sn–Cu solder. In the first set, a gradual increase in metal leaching was observed with an increase in acid concentration approaching complete metal leaching at an acid concentration 80%. It is worthy to note that 68 (± 0.58) and 70 (± 0.72) % metal leaching was obtained for Cu and Sn, respectively, at 10% acid concentration (Fig. 2a). These results suggest that the low concentrations of acetic acid are also effective for metal dissolution. A similar effect of an increase in the concentration of nitric acid on metal leaching from solder was reported by Yoo et al. (2012). The high concentration of leaching solution facilitates a more acidic environment which is essential for transmission and exchange of ions. This will help for the rapid extraction of metals (Kirpichtchikova et al. 2006; Mohanty and Mahindraker 2011). These results encourage the development of a two-step industrial process. The first step will produce the acetic acid using microorganisms. Further, in the second step, the acetic acid can be used for leaching of metals. In this way, a combination of hydro- and biohydrometallurgical processes can be applied for leaching of metals from solders. Several microorganisms produce acetic acid. *Acetobacter* and *Gluconacetobacter* are the main genera involved in the acetic acid production. Acetic acid bacteria (AAB) are strict aerobes that belong to Alphaproteobacteria. They have an ability to partially oxidize carbon sources into a corresponding organic compound, such as ethanol to acetic acid (Wang et al. 2013; Qi et al. 2014; Gullo et al. 2014). Acetic acid production usually requires lower capital investment and shorter start-up times. Furthermore, the raw materials (e.g., Corn, sugarcane, and sugar beet) are a renewable resource (Cheryan 2009). The acetic acid content differs depending on microbial culture; type of substrate used; and culture conditions. Several researchers reported production of 4 to 10% acetic acid (Sievers et al. 1992; Gullo et al. 2009; Mamlouk et al. 2011; Schleputz et al. 2013). Considering an amount of acetic acid produced by microorganisms, another set of experiment was carried out by varying the acetic acid concentration (2–10%). Again the metal leaching increased with an increase in acetic acid concentration. A 34 (± 1.05) and 49 (± 0.1)% metal leaching was achieved for Cu and Sn, respectively, using 4% acetic acid with 100/10 (mg/ml) solid-to-liquid ratio (Fig. 2b). These results suggest that both the hydro- and biohydrometallurgical processes can be established depending on the concentration of acetic acid used, for leaching of metals from Pb-free solders. Since in the present study, 80% acetic acid concentration was found optimum for leaching of 100% Cu and Sn, respectively, it was used in further studies to optimize process parameters.

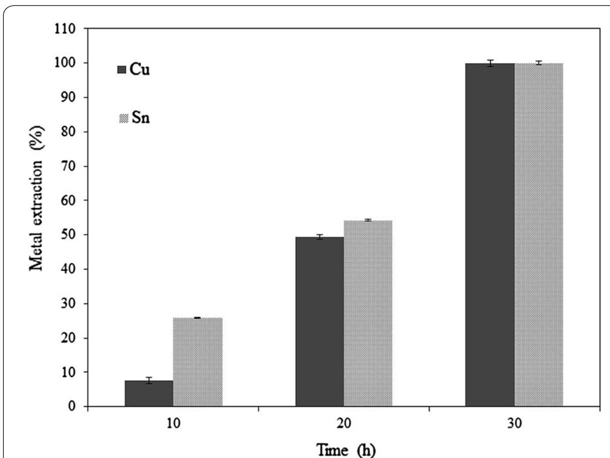

Fig. 1 Time period evaluation of metal recovery from Sn–Cu solder (100 mg) by 10 ml acetic acid (100%) at 150 rpm shaking speed and at 30 °C temperature

The effect of acetic acid volume on the solder leaching efficiency

An experiment was carried out to study an effect of the volume of acetic acid (80%) on metal removal from Sn–Cu solder. It was found that 4 ml acetic acid was optimum for 100% metal leaching from Sn–Cu solder (100 mg) in 30 h (data not shown).

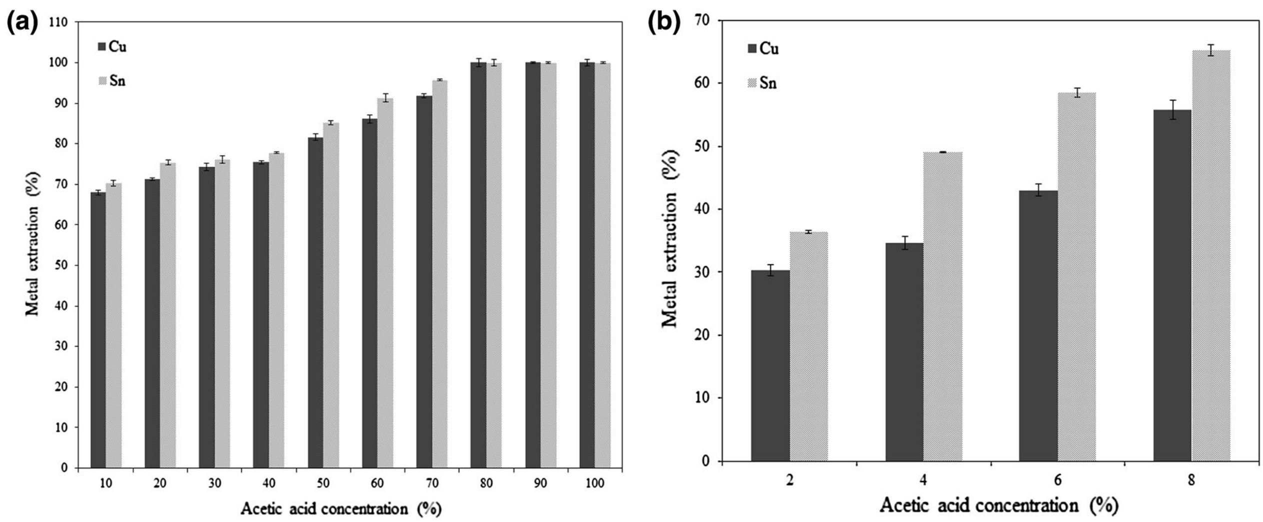

Fig. 2 Effect of concentration of acetic acid **a** 10–100% and **b** 2–8%, on metal recovery from Sn–Cu solder (100 mg) by 10 ml acetic acid at 150 rpm shaking speed at 30 °C temperature and 30 h incubation

The effects of shaking speed on solder leaching efficiency

Effect of shaking speed on metal removal from Sn–Cu solder was studied. It was observed that with an increase in shaking speed the metal leaching also increased. At static condition, only 2 (± 0.16) and 5 (± 0.6)% metal leaching was observed for Cu and Sn, respectively. With an increase in shaking speed to 100 rpm, the metal leaching also increased to 56 (± 1.8) and 58 (± 0.18)% for Cu and Sn, respectively. At shaking speeds 150 and 200 rpm, 100% metal leaching was observed for Cu and Sn, respectively (Fig. 3). Therefore, in further experiments, shaking speed of 150 rpm was used. The higher agitation speeds keep mineral particles in a suspended state (Espiari et al. 2006). Therefore, more metal leaching was observed at 150 rpm. Hocheng et al. (2014) reported similar results, while Yoo et al. (2012) found that metal dissolution was independent of shaking speed.

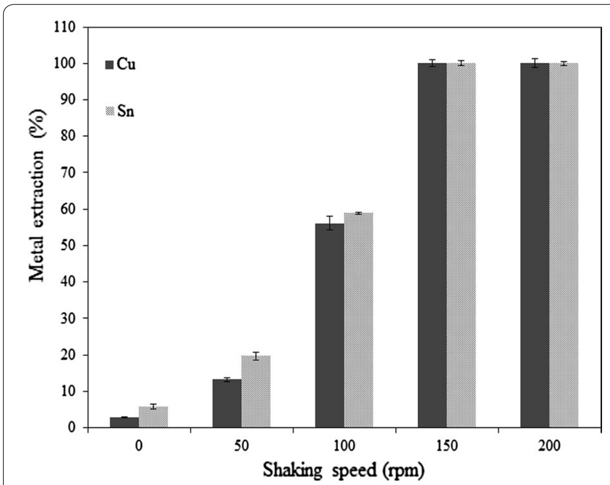

Fig. 3 Effect of shaking speed on metal recovery from Sn–Cu solder (100 mg) by 4 ml acetic acid (80%) at 30 °C temperature and at 30 h incubation

The effect of temperature on solder leaching efficiency

Figure 4 shows an effect of leaching temperature on the metal leaching from Sn–Cu solders. The dissolution temperature was varied in the range of 30–50 °C, while all other parameters were kept constant. Complete metal leaching was observed at 30 °C. The metal leaching decreased with an increase in temperature after 30 °C. These results are contrary to Barakat (1999) and Yoo et al. (2012) who found that the higher temperatures yielded higher dissolution efficiencies. These authors used different acids. A loss of volume can occur for acetic acid at higher temperatures. This might have affected the metal leaching process.

The effect of particle size on the solder leaching efficiency

Different sizes of Sn–Cu solder pieces like 3, 5, and 7 mm were used to study the leaching efficiency. The obtained results suggest that the rate of metal leaching decreased with an increase in particle size due to decreased contact surface area. For the 7-mm size solder pieces, the 94 and 96% Cu and Sn leaching were observed, respectively (Fig. 5). Hasani et al. (2017) found that Pt dissolution from automotive catalytic converters increased significantly with decreasing particle size, due to smaller particles providing larger contact surface area between solid and the leaching reagent.

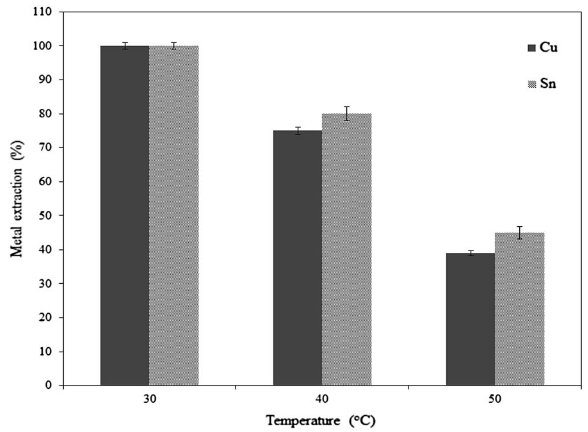

Fig. 4 Effect of temperature on metal recovery from Sn–Cu solder (100 mg) by 4 ml acetic acid (80%) at 150 rpm shaking speed and 30 h incubation

The effect of solder weight ratio on leaching efficiency

An effect of increasing solder weight, ranging from 100 to 900 mg, was investigated under the leaching conditions of 4 ml acetic acid, at 150 rpm, at 30 °C. The metal leaching decreased with an increase in solder weight. Still, it was possible to achieve 90 (± 1.2) and 95 (± 0.86)% metal leaching while using 500 mg solder (Fig. 6). These results are comparable with Yoo et al. (2012) and Hocheng et al. (2014). A lack of sufficient acid at an increased pulp density is responsible for the decrease in leaching efficiency (Aung and Ting 2005; Mehta et al. 2010; Hocheng et al. 2014).

The effect of microbially produced acetic acid on the solder leaching efficiency

The leaching efficiency of acetic acid was further compared with the acetic acid produced by *Acetobacter* sp. *Acetobacter* sp. was found to produce 5% acetic acid as estimated by the method described by Beheshti Maal and Shafiei (2010) (data not shown). It is in accordance with the literature which suggests the biological acetic acid production in the range of 4–10% (Sievers et al. 1992; Gullo et al. 2009; Mamlouk et al. 2011; Schleputz et al. 2013). *Acetobacter* sp. was grown for sufficient incubation period and the culture supernatant was collected. This culture supernatant was used for leaching of Cu and Sn from solder. The results suggest that 39 and 54% leaching of Cu and Sn were obtained, respectively, using *Acetobacter* sp. culture supernatant (Fig. 7). Although the obtained metal leaching efficiency using *Acetobacter* sp. culture supernatant is less as compared to 80% acetic acid, still a fairly good leaching efficiency is observed (Figs. 2a, 7). These results show that the *Acetobacter* sp. can play a significant role in bioleaching process for resource recovery not only from waste solder but also from other industrial wastes.

SEM analysis

Scanning electron microscopy was used to analyze the surface of solder during leaching process using 80% acetic acid (Fig. 8). Control samples show the smooth surface of solder particles. But the surface of solder after 10-h leaching treatment is very rough and deteriorated

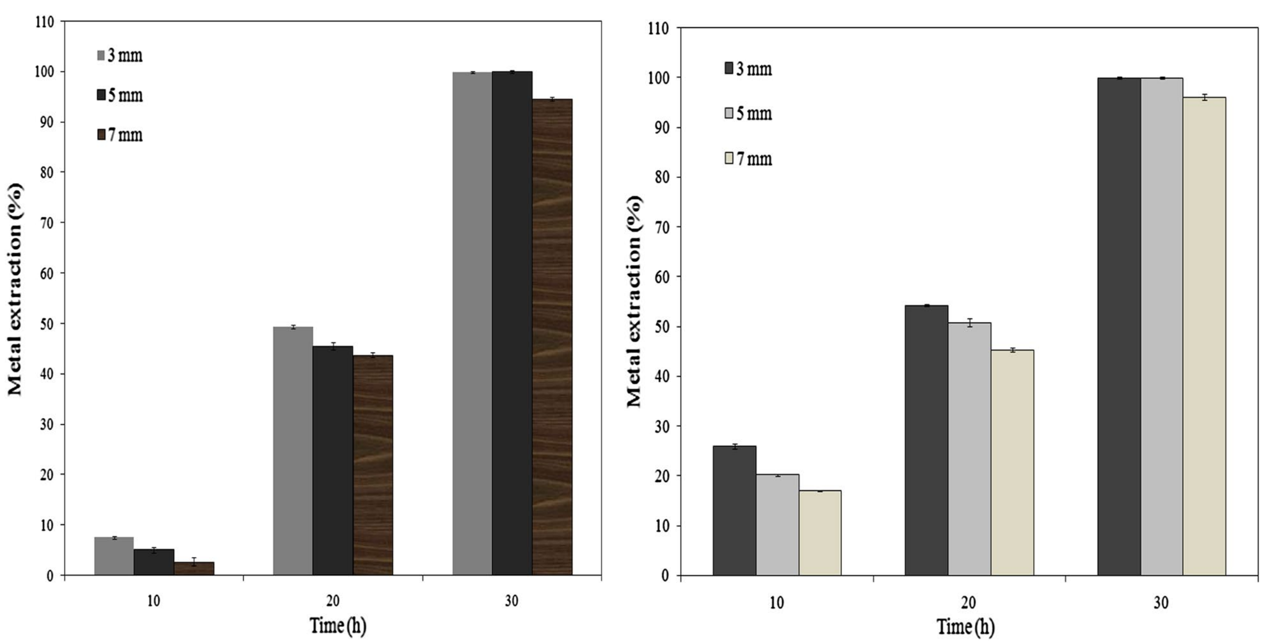

Fig. 5 Effect of particle size of Sn–Cu solder on metal recovery from by 4 ml acetic acid (80%) at 150 rpm shaking speed at 30 °C temperature and 30 h incubation

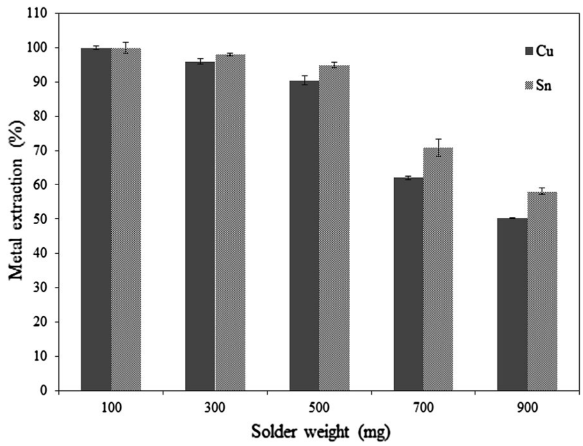

Fig. 6 Effect of increasing weight of Sn–Cu solder on metal recovery from by 4 ml acetic acid (80%) at 150 rpm shaking speed at 30 °C temperature and 30 h incubation

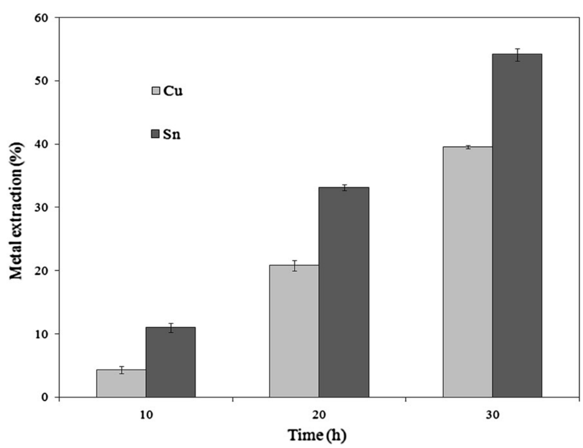

Fig. 7 Effect of microbially produced acetic acid on metal recovery from Sn–Cu solder (100 mg) at 150 rpm shaking speed and 30 h incubation

suggesting the removal of metals from the solder surface. Further, the 20 h sample shows the degraded and smooth surface suggesting nearly complete metal removal. Moreover, the EDS analysis shows only the presence of Sn in control samples and Cu appears to be present after treatment, suggesting the presence of Sn alone in the upper coating of solder and mixture of Sn and Cu in the core, which is released after the upper layer is eroded.

The results of present study showed that the acetic acid can be used for leaching of metals from lead-free solders. The metal leaching efficiency using acetic acid was better for Sn–Cu solder compared to Sn–Cu–Ag solder. The 100% metal leaching from Sn–Cu solder was achieved using 80% acetic acid at 150 rpm in 30 h at 100 mg/4 ml pulp density. The 10% acetic acid concentration was found useful as well for metal leaching (68 and 70% Cu and Sn, respectively).

Recent reports suggested that the alternative Pb-free solders are more harmful to the environment than Sn–Pb solder (Cheng et al. 2011). Unfortunately, most research until now is focused on leaching performance of heavy metal elements in lead-containing solder (Subramanian et al. 1995; Hin et al. 1997; Ramsay et al. 2002) and only a few studies have reported leaching behavior of alternatives solders (Yoo et al. 2012; Hocheng et al. 2014). A comparison of the present study with reported literature is shown in Table 2. Yoo et al. (2012) reported a hydrometallurgical process for leaching of metals from Sn–Cu–Ag solder. Hocheng et al. (2014) reported a bioleaching process for leaching of metals from Sn–Cu–Ag and Sn–Cu solders. A comparison of the present method with these reports clearly indicates that the efficiency of a process depends on the type of solder material, type, and concentration of lixiviant used. Yoo et al. (2012) required less time for metal leaching from Sn–Cu–Ag solder. But their process has certain limitations. A high temperature is required (75 °C) for their process. Also, they used nitric acid as a leaching agent (Table 2). This leads to a threat to the environment. NOx is released during the leaching process. This process also generates the wastewater containing high concentrations of inorganic acid (Li et al. 2010). The bioleaching process requires more time for metal leaching from Sn–Cu solder (Table 2). In this context, the present method is more advantageous since it is possible to carry out the process at 30 °C. Also, an organic acid (acetic acid) was introduced as leaching reagent. Acetic acid is a low molecular weight organic acid (weak chelating agent) (Gzar et al. 2014). Organic acids degrade easily under aerobic and anaerobic conditions as compared to HCl, HNO_3, and H_2SO_4. Due to this property of organic acids, the waste solutions remaining after the leaching process can be treated easily.

Conclusions

This study reveals an effective process to recycle the Pb-free solders. The metals in industrial waste are often present as oxides rather than sulfides. These metal oxides can only be leached by acids. Application of organic acid (acetic acid) for metal leaching provides a suitable and economic alternative. An increase in reaction time increased the leaching efficiency. The concentration of acetic acid greatly affects the leaching efficiency. The results suggest that the low concentrations of acetic acid are also effective for metal dissolution. The use of high temperature is not favorable for metal leaching process since the loss of acetic acid volume occurs at high

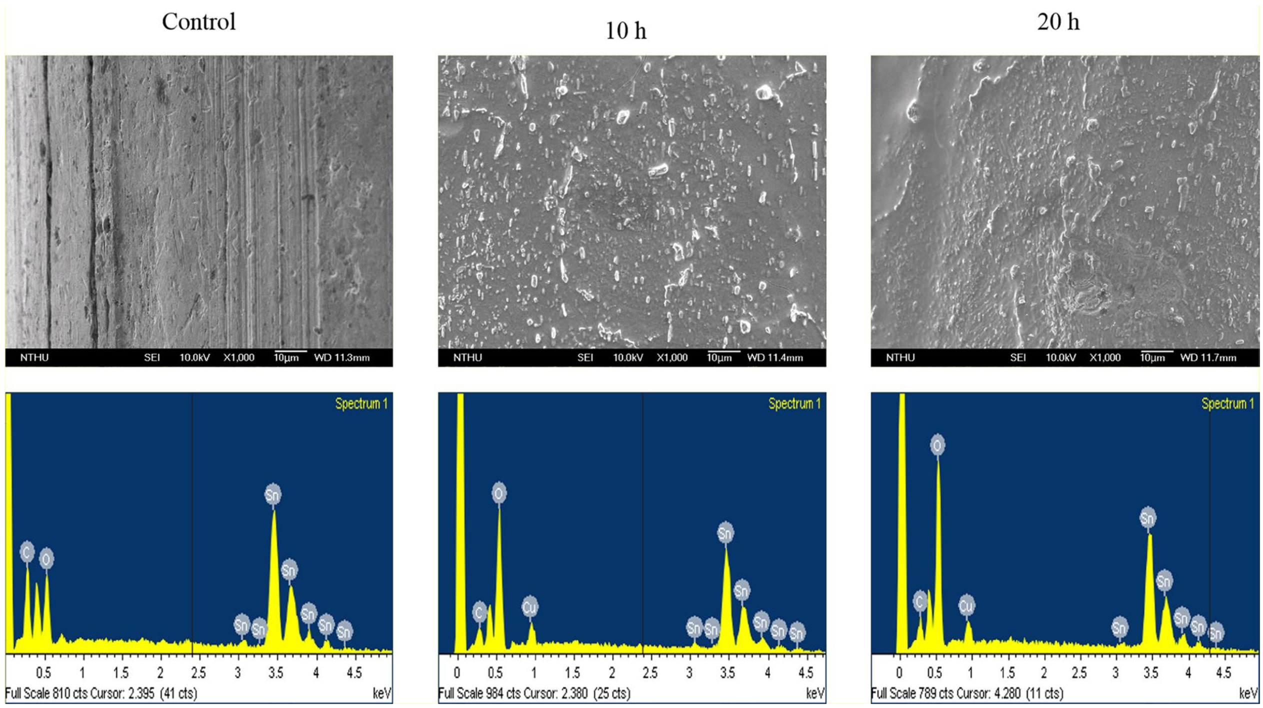

Fig. 8 SEM-EDS analysis of the Sn–Cu solder surface during acetic acid leaching

Table 2 Comparison of present study with existing literature

Sr. no.	Solder type	Lixiviant used	Concentration of lixiviant	Amount of solder used (g/L)	Temperature (°C)	Amount of metals recovered (%)	Time required (h)	References
1	Sn–Cu	Acetic acid	80%	25	30	100	30	Present study
2	Sn–Cu	*A. niger* culture supernatant containing citric acid	20 g/l	5	30	100	96	Hocheng et al. (2014)
3	Sn–Cu–Ag	*A. niger* culture supernatant containing citric acid	20 g/l	5	30	100	48	Hocheng et al. (2014)
4	Sn–Cu–Ag	Nitric acid	2 M	100	75	100	2	Yoo et al. (2012)

temperatures. But this factor is beneficial for establishing an industrial process due to less demand for energy. Also, a fair good amount of metal leaching was achieved at high pulp densities.

Authors' contributions

HH and UJ put forth the idea for the research carried out in the manuscript. SC helped in carrying out the experiments. MC was involved in editing and submission of the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analyzed during this study are included in this article.

Consent for publication

The authors approved the consent for publishing the manuscript.

Ethics approval and consent to participate

The authors affirm that they read the manuscript and approved the content of the manuscript submitted for publication and are accountable for all aspects of the accuracy and integrity. This article is original and has not been published so far in any other journal.

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