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Journal of Hazardous Materials 58 (1998) 179–194
JOURNAL OF HAZARDOUS MATERIALS

Characterization of vitrified slag from mixed medical waste surrogates treated by a thermal plasma system

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Abstract

Various mixed medical waste surrogates have been vitrified by a plasma system built at Institute of Nuclear Energy Research (INER) in Taiwan, Republic of China. Characterizations of vitrified slag were carried out in order to evaluate the effectiveness of an indirect plasma heating used in the INER system. After vitrification, a monolithic metal nugget was separated from the vitrified slag as a result of the gravity effect. The vitrified slag consisted of mostly amorphous state of SiO_2, which in turn dissolved other minor constituents from waste feeds and crucible container. In the slag, dispersive metal-bearing second phases in different shapes were observed. Due to their insoluble nature, these phases were embedded in the slag matrix, and no macroscopic segregation was detected. This observation indicates the presence of mixing state during the vitrification treatment. The formation of second phases was closely related to the metallic waste treated, as evidenced by the increased slag densities for the high metallic feed samples. Leachability analysis results revealed that the encapsulation of these second phases by the slag matrix was very effective. Therefore, with optimal feed compositions, the indirect plasma heating condition used in this study has been shown to be satisfactory for the thermal vitrification of mixed medical wastes. © 1998 Elsevier Science B.V.

Keywords: Vitrified slag; Mixed medical waste surrogates; Thermal plasma system

1. Introduction

Medical waste disposal practices being used to date are expected to have major changes in the future to cope with progressively stringent regulatory requirements and

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PII S0304-3894(97)00130-1

increasing public concerns over the recent AIDS (acquired immune deficiency syndrome) dilemma and other communicable diseases such as hepatitis B [1]. The public concerns also come from the difficulty, as well as complexity, over the handling of medical waste due to its heterogeneity in nature. Depending on the sources where the wastes are generated, the types of medical waste vary considerably; they may include anatomical, pathological, infectious, radioactive and other types of waste [1]. These variations have a dramatic impact on the selection and performance of technologies for treatment. For instance, the conventional incineration is not suitable for treating non-combustible waste; thus, pre-sorting of waste is required. In addition, the ash residue from incineration needs further consolidation prior to proper landfill disposal.

The emergence of thermal plasma technology in recent years has received a great deal of interest for its many advantages when used for treating mixed forms of waste. A plasma, defined as an electrically conductive 'gas', is commonly referred to as the fourth state of matter [2,3]. The plasma generates high temperatures and is often regarded as one of the cleanest heat sources. Thus, it is well suited for an incredibly diverse range of applications [2,3]—from microelectronics, material chemistry analysis, metal refining, destruction of organics, to the recent development of plasma vitrification of hazardous wastes [4]. As shown by many studies [4], the plasma is used to encapsulate inorganic hazardous materials in either a glassy slag or a glass, depending on the overall chemistry of the feed, and render the treated products with desirable properties for direct final disposal. These properties are very low leachability, high volume reduction and high strength. Since the plasma vitrification can be performed in many atmospheric conditions (such as air, Ar, N_2) and at high temperatures $\geq 1500°C$, the waste forms become flexible; not only the combustible but also the wide variety of waste streams, such as liquids, gases, solids, slurries, concrete and drummed wastes can be treated with good results.

In light of the recent advancement aboard, a lab-scale plasma system has been built at the Institute of Nuclear Energy Research (INER) in Taiwan. For the feasibility study, preliminary test runs have been performed on a number of wastes, including cement–solidified radioactive waste surrogates, ash from power plant, slurries and dusts from steel mill [5]. As part of the feasibility study, this research is directed toward a better understanding of application of thermal plasma to the medical waste treatment. The medical waste was selected because of the public concerns, as described above, and the fact that the medical wastes contain various combustible and noncombustible materials, and results from this study can yield an indication for the flexibility of waste treated by the INER plasma system. Due to lack of material characterization details for the vitrified products, such indication given in a similar study reported elsewhere [6] becomes somewhat inconclusive.

To facilitate the evaluation of the system to effectively vitrify various constituents within the surrogates into a nonleachable glassy slag, zinc, selected as a tracer metal, was spiked in the form of zinc oxide (ZnO) into the surrogate before treatment [7]. After the plasma vitrification, the slag was characterized by scanning electron microscopy (SEM) with backscattered electron imaging (BEI) for microstructure/morphology observation, energy dispersive spectroscopy (EDS) for X-ray chemical microanalysis, and X-ray diffractometry (XRD) for crystal structure/chemistry determination. The treated products were also subjected to the toxicity characteristic leaching procedure (TCLP), followed by a leachability analysis for the selected elements using atomic absorption spectrometry (AAS). Meaningful mass balance results were not possible to obtain in this study due to severe crucible erosion problems. To further verify the efficiency of INER system, offgas as well as other slag properties such as strengths were also characterized extensively, and their results will be presented elsewhere (Chu et al., to be published).

2. Experimental

A schematic description of the INER plasma system is shown in Fig. 1. The heat source was a 100 kW non-transferred arc-generated plasma torch, as shown in Fig. 2. Temperatures at the centerline of plasma could be in excess of 10 000°C and with electron density of $6 \times 10^{22}/m^3$. Power efficiency of plasma torch was at least 85% [5]. Ar was the plasma gas for ignition and, after ignition, air was used during the treatment. The desired temperature was achieved by controlling air flow rate and dc plasma

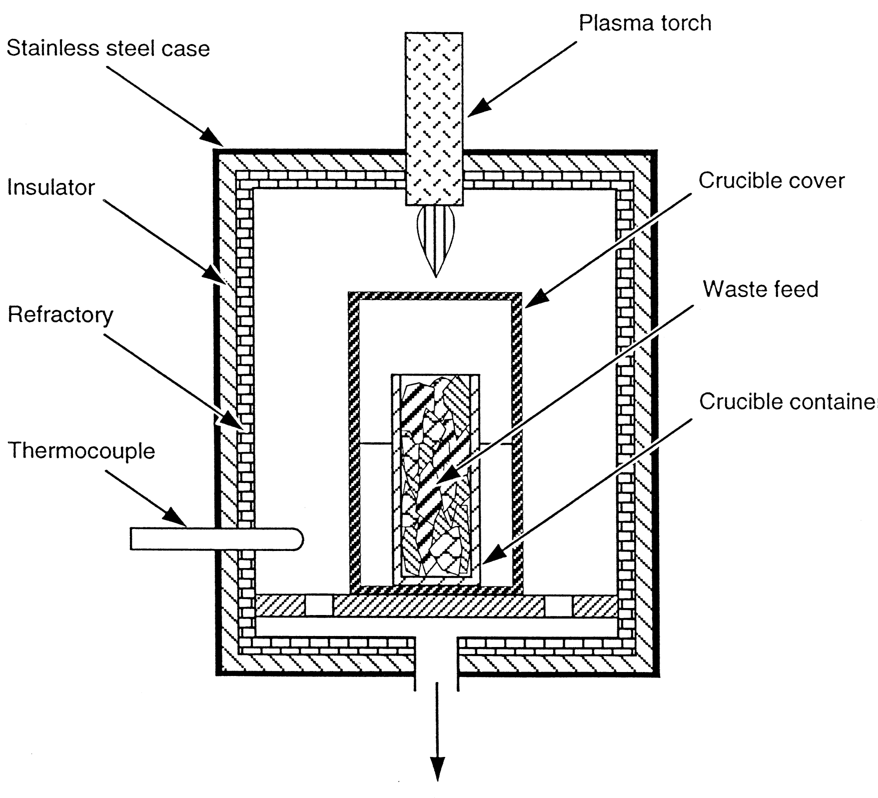


Fig. 1. A schematic description of the INER plasma vitrification system used in this study.

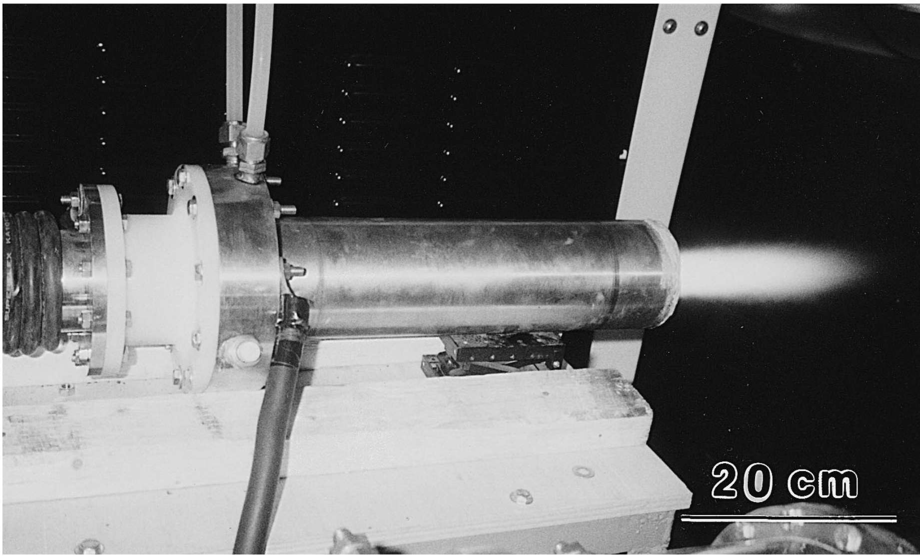


Fig. 2. A photograph showing a plasma torch operated at 100 A and 500 V. The visible plasma was ~20 cm long. Air was used as plasma gas at flow rate of 300 standard l/min.

current. The chamber was designed so that the optimal uniform temperature distribution was obtained and the temperature measured by a thermocouple was approximately equivalent to that at the crucible container where the waste was placed. Due to the high-pressure plasma gas, the waste was covered with a crucible to avoid an overflow or spreading during the treatment. The cylindrical crucible container (10 wt.% Cr_2O_3 and 90% Al_2O_3) had a size of $63\phi \times 105$ mm, resulting in the waste feed of ~400–500 g, depending on the waste composition.

The waste surrogates were categorized into two groups: combustible (pork ribs, tongue press, gauzes, swabs and absorbents) and noncombustible (glass, stainless steel, sharps, needles and syringes). Table 1 lists seven different feed combinations treated in this study, along with slag density and TCLP results. For each feed, the pork rib, glass

Table 1
List of feeds treated in this study, along with slag density and TCLP analysis results for Cr and Zn

Sample	Feeds[a]	Slag density (g/cm^3)	Vitrified slag leachate	
			Cr (mg/l)	Zn (mg/l)
No. 1	1:1:1	2.75	0.68	0.074
No. 2	2:1:1	2.76	2.1	0.30
No. 3	1:2:1	2.72	0.53	0.081
No. 4	1:1:2	2.85	0.46	0.094
No. 5	3:1:1	2.94	1.1	0.65
No. 6	1:3:1	2.60	0.27	0.12
No. 7	1:1:3	2.87	0.27	0.091

[a] These ratios represent those of stainless steel:glass:pork rib in weight.

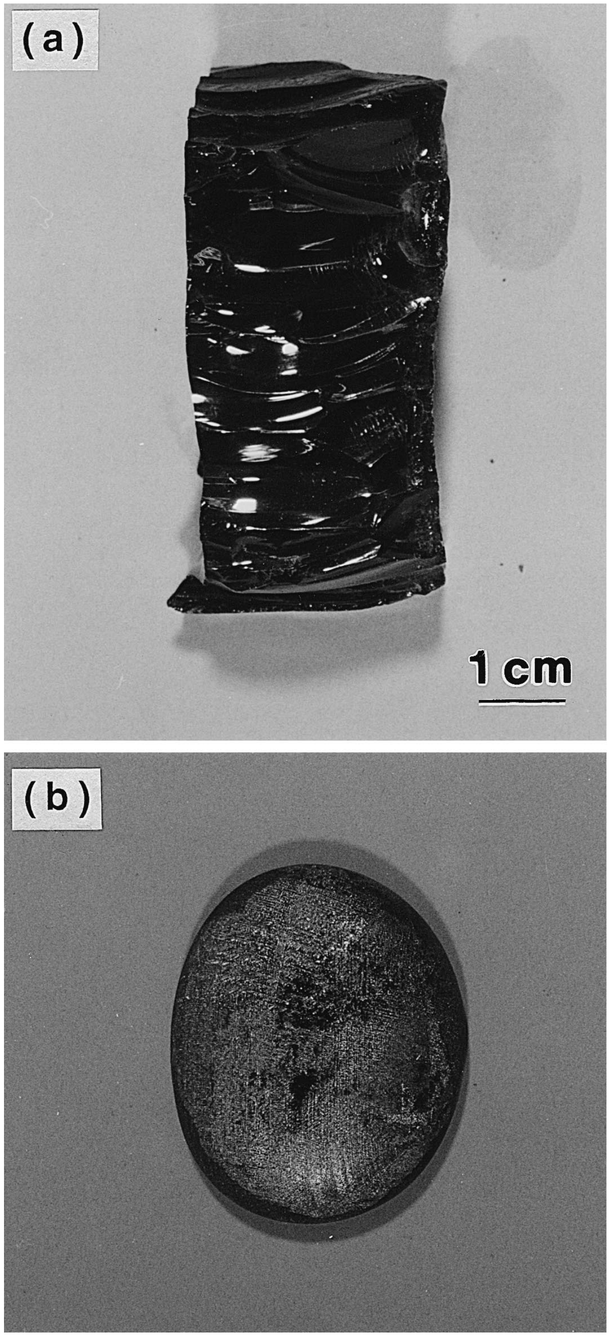
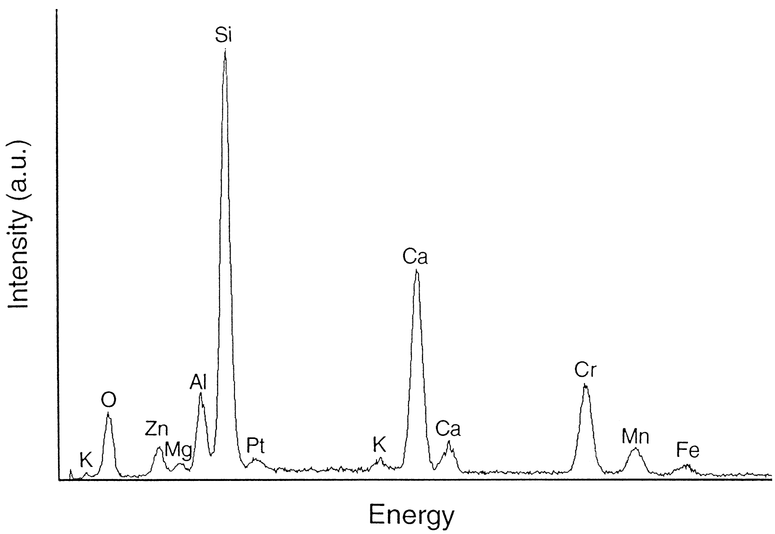


Fig. 3. Optical photographs of plasma vitrified slag (a) and metallic nugget (b).

and stainless steel varied while other additives (gauzes, swabs, syringes and needles) were kept the same weight. Prior to treatment, 28,000 ppm ZnO ($\sim$ 11–14 g) were added to the feed. The vitrification treatment lasted 15 min at 1550°C. To alleviate thermal shock damages, the heating/cooling rates were maintained < 10°C/min. After cooling to room temperature, the vitrified slag was characterized. Analytical tools used were SEM, BEI and EDS on a field-emission Hitachi S-4100 scanning electron microscope, XRD on a Siemens D5000 diffractometer with monochromatic Cu-K_{α} radiation, and, after TCLP, AAS on a Hitachi Z-8230 atomic absorption spectrometer.

3. Results and discussion

After plasma vitrification, the products consisted of two macroscopic components—vitrified glassy slag and ellipsoidal metal nugget. These typical products are shown in



Element	Atom %
O-K	46.0
Si-K	21.0
Ca-K	12.8
Cr-K	8.8
Al-K	4.1
Zn-K	2.8
Mn-K	1.8
Fe-K	1.2
Mg-K	0.7
K-K	0.5
Pt-M	0.3
Total	100.0

(a)

Fig. 4. (a) A typical EDS analysis result of plasma-vitrified glassy slag; (b) XRD results of as-vitrified slag in bulk form; (c) in powder form.

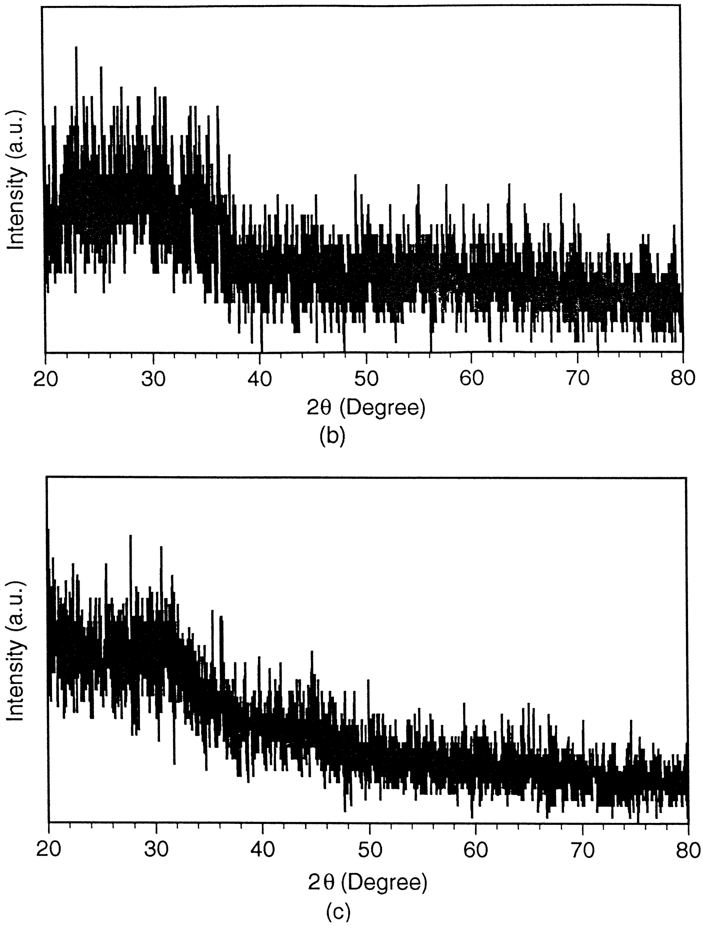
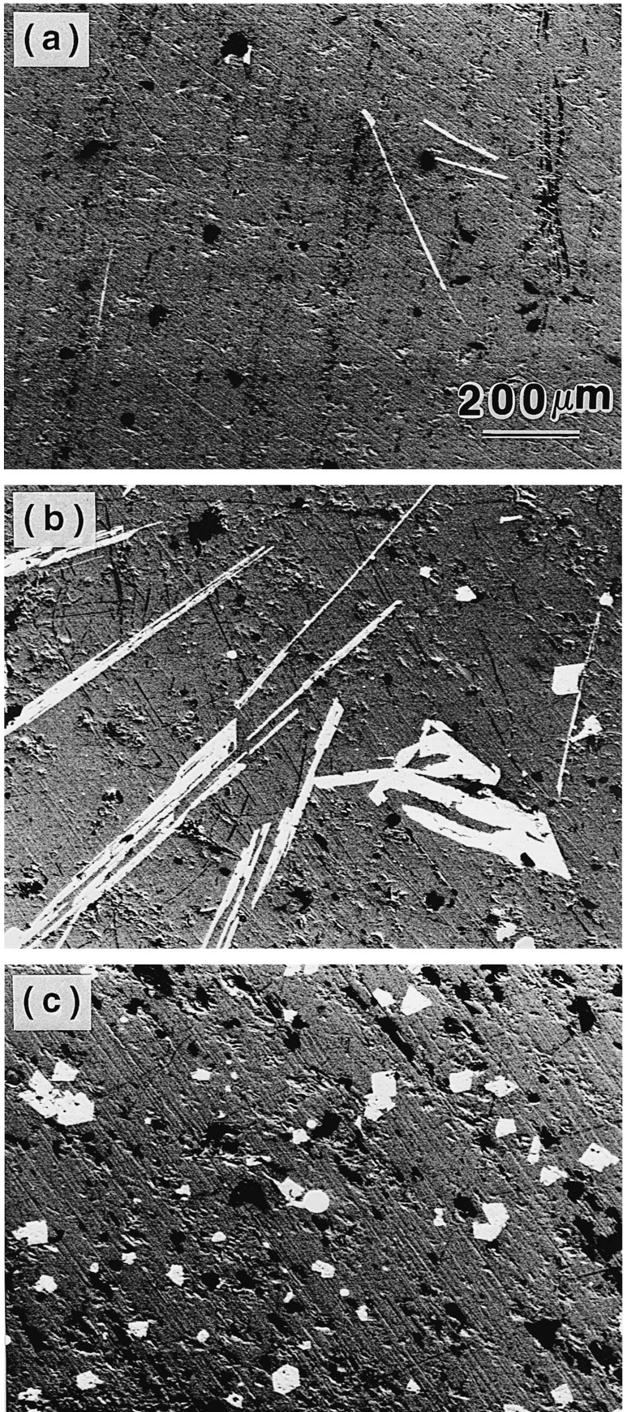
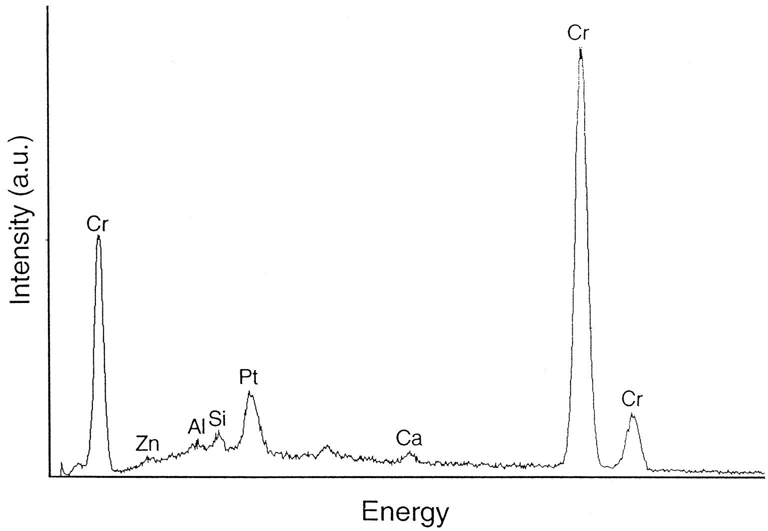


Fig. 4 (continued).

Fig. 3. According to the appearance, each phase revealed no distinct segregation except for samples no. 2 and no. 5. For these two samples, ZnO powder (~ 6–7 g) were found on the top periphery of the crucible, presumably resulting from relatively high contents of metallic waste that were not properly vitrified. The separation of glassy slag and metal nugget was considered to be a result of specific gravity difference between these macroscopically homogeneous masses. The way in which the metal nugget separated from the glassy slag gives the clue to the metal recovery achieved by the INER plasma system, similar to other plasma techniques reported previously [2]. EDS analysis results (Fig. 4a) indicated the glassy slag contained mainly Si, Ca, Cr and Al. Si was from glass wastes, Ca from pork rib, Cr from stainless steel and erosion of crucible, and Al from crucible erosion. Since the major constituents were Si and O, this slag was determined as mostly SiO_2. XRD results of bulk slag shown in Fig. 4b indicated the amorphous state of slag, further confirming the glassy slag of SiO_2. After pulverization, the slag


(a)
200 μm
(b)
(c)



Element	Atom %
Cr-K	91.8
Si-K	4.3
Al-K	2.5
Ca-K	1.1
Zn-K	0.3
Total	100.0

Fig. 6. EDS analysis result of plate-shaped second phase present in vitrified no. 5 slag.

powder still exhibited the amorphous nature and no major crystalline structures or phases were observed (see Fig. 4c).

When examined with SEM in BEI mode, the glassy slags revealed no major segregation but were dispersed with various second phases. The formation of second phases appeared to vary with the feed composition. With different feed compositions, typical BEI micrographs taken from no. 6 and no. 5 slags in Fig. 5 clearly show such microstructural variation. For the feed with fewer metals (sample no. 6), the slag showed very few observable second phases. In contrast, for the high metal feed (sample no. 5), the slag exhibited numerous second phases. These dispersed second phases included spheroids, plate (or needle) and irregular-shaped phases. For the plate-shaped phases, customarily called Widmanstätten structure in the precipitation of alloys [8], the EDS analysis results (in Fig. 6) indicated that Cr was the major constituent, with Si, Al, Ca and Zn as minor elements. Spheroids predominantly consisted of Fe, P and Cr, as evidenced by an SEM micrograph with Fe X-ray microanalytical mapping image and EDS analysis results in Fig. 7. Irregular-shaped Cr-rich phases were also found in a high metal-content slag (see Fig. 8). The irregular shapes imply that these phases were not

Fig. 5. BEI micrographs of plasma vitrified slags from samples no. 6 (a) and no. 5 (b), (c).

thoroughly melted, presumably due to a higher melting point, and were mixed with slag during vitrification, eventually embedded in the slag matrix after solidification. Primary elements of these phases were the tracer element and those from waste feed and crucible, according to the EDS results. Fe was from stainless steel, Cr from both stainless steel and crucible container erosion, Al also from the crucible erosion, P and Ca from pork rib, whereas Pt was from an electrically conductive thin coating applied on the slag sample for SEM examination. Dispersions of Fe-rich spheroids, Cr-rich irregular and plate-shapes phases in the slag suggest the presence of mixing state of the elements from waste feeds and crucible within the vitrified slag during the treatment, as

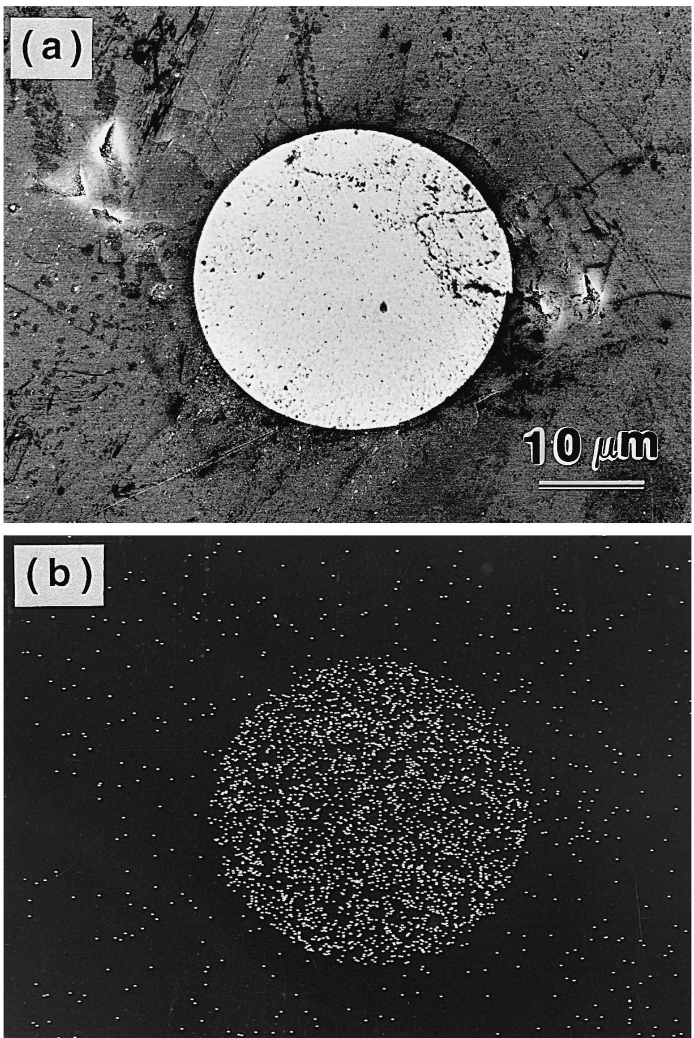
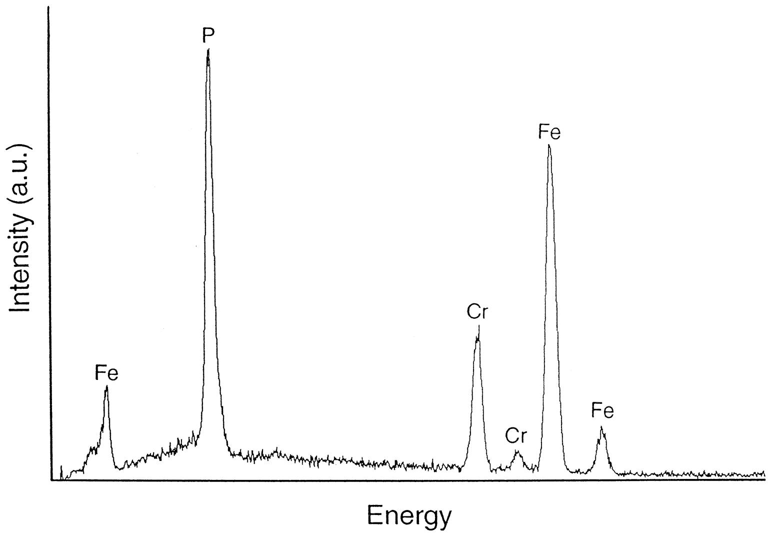


Fig. 7. (a) SEM micrograph, (b) Fe X-ray microanalytical mapping image and (c) EDS analysis result of plasma vitrified slag from sample no. 5, showing Fe-rich spheroid second phase.



Element	Atom %
Fe-L	44.9
P-K	37.0
Cr-K	18.1
Total	100.0

(c)

Fig. 7 (continued).

a result of high-temperature driven diffusion effects. Consequently, these elements formed alloys or compounds that were not soluble with the slag at room temperature, resulting in spheroids and other shaped phases in the slag matrix. Spherical shape of Fe-rich phase was attributed to the reduction of surface free energy during solidification [8].

Based on the above findings, it is proposed that the plasma vitrification resulting in a rather uniform mixing of waste feeds after combustible components were incinerated during treatment, and insoluble metal-bearing second phase dispersions occurred in the slag upon solidification. The ellipsoidal metal nugget separated from the glassy slag due to the gravity effect during the treatment. Fig. 9 shows a schematic illustration of different stages for incineration, melting, mixing, vitrification and separation. Since the distinct transition from one stage to another is difficult to define, each stage was allocated approximately according to the treatment temperature monitored. The vitrification started at early stage of treatment; thus, the molten pool of slag picked up the constituents in contact due to the high-temperature enhanced diffusion effects. Accordingly, the glassy slag contained numerous constituents, including those from the crucible. When the metallic components began to melt or oxidize, the diffusion and the pick-up of constituents within the molten pool were at maximum because most of materials at this stage were in the molten state. Meanwhile, the molten pool underwent vigorous mixing since the heavy molten metals tended to settle at the bottom where the slag was present before the metals were melted, whereas the light-weighted slag moved toward the top. As a result, the molten slag pool dissolved or picked up metal components when they were reshuffling, and these components precipitated out from the slag matrix during the final stage of solidification because of very limited solubilities at room temperature. The precipitation of dispersed second phases is commonly found in many alloys with finite solubilities of precipitates [8].

Although no rotating hearth or stirring coil devices were equipped for mixing enhancement of the melt, the macroscopically homogenous state of vitrified slag has been achieved with the INER plasma system. In addition, indirect plasma heating used

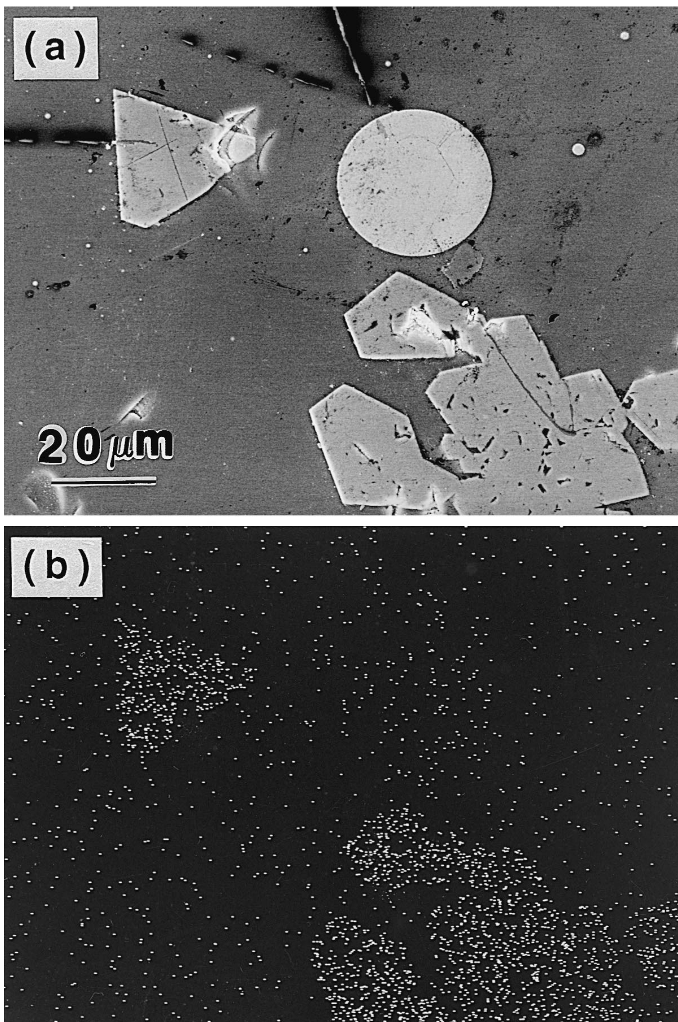
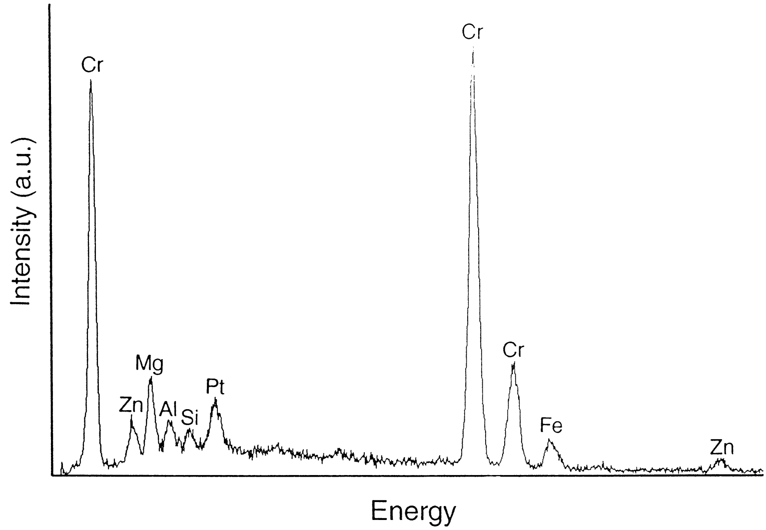


Fig. 8. (a) SEM micrograph, (b) Cr X-ray microanalytical mapping image and (c) EDS analysis result of plasma vitrified slag from sample no. 5, showing Cr-rich irregular-shaped second phases.



Element	Atom %
Cr-K	63.6
Mg-K	12.4
Zn-K	9.3
Fe-K	6.5
Al-K	4.9
Si-K	3.3
Total	100.0

(c)

Fig. 8 (continued).

in this study generated no forces from plasma gas exerting upon the waste, distinctly different from the direct heating mode of most plasma vitrification studies [4]. The achievement of homogenization in this study is thus considered to be primarily resulting from the heat convection and reshuffling within the molten state of treated materials. This gives a good indication of effectiveness of thermal vitrification of mixed wastes when the treatment temperature is sufficiently high, and the enhancement for blending by an external means seems to be less important. However, the use of external forces becomes necessary to improve the vitrification efficiency in the case that the temperature is not adequately elevated, or the melt viscosity is too high [9].

Slag densities shown in Table 1 reveal no considerable variations with the feed, although they tended to be higher as the glass in the feed decreased. According to SEM observations, the second phases dispersed within the slag matrix might have caused the increase in the slag density. To visualize this second phase effect, samples no. 6 and no. 5 were compared. About 10% of increase in slag density was found as a result of increased metallic-bearing phases in the slag of high steel feeds. In addition, the slag density increased with the pork rib quantity (see samples no. 4 and no. 7 in relation to no. 6). Thus, the increase in the second phases was correlated well with the increased

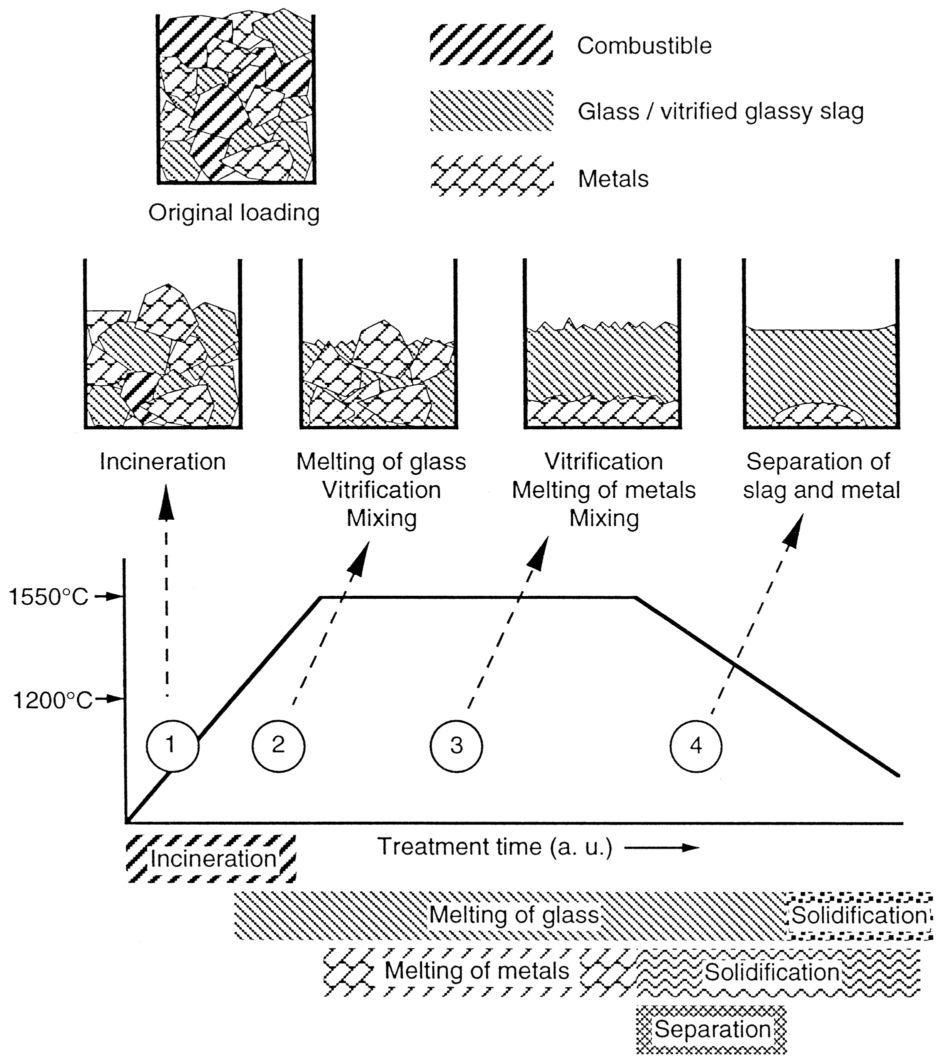


Fig. 9. A schematic illustration depicting different stages of (1) incineration, (2) and (3) melting, mixing, vitrification and (4) separation for the plasma vitrification treatment.

slag density. The correlation implies that the vitrified glassy slag chemistry and density changed due to the encapsulation of increased inorganic materials when more inorganic were fed, signifying the important role of vitrified slag on treating inorganic-bearing mixed wastes.

TCLP analysis results of the vitrified slag are given in Table 1. Except for samples no. 2 and 5, each sample slag exhibited insignificant leachability characteristics for the Cr and spiked Zn. Therefore, the encapsulation of insoluble metal-bearing second phases by the slag matrix is regarded very effective in preventing them from leaching out. For the no. 2 and 5 samples, relatively high Cr and Zn concentrations in the leachate were attributed to the combined effect of high volume fractions of second phases present in the slag, and incomplete vitrification of ZnO that led to the ZnO residing on the top of slag. Accordingly, the optimal feed combinations determined in this study were those with the metallic components less than 40% of feed in weight. As a comparison, Zn leachate concentrations obtained in this study (with the exception of no. 2 and 5 samples) were about an order of magnitude lower than those reported in vitrified soils using a centrifugal hearth plasma system [7]. The reduced leachate concentrations may have resulted from the difference in the overall chemistry of the feed. ∼ 20–50 wt.% of the feeds in our study were glass, while the contaminated soils were the major constituent in the plasma vitrified soil study [7].

4. Conclusion

An indirect plasma heating has been effectively utilized in the INER system for thermal vitrification of mixed medical waste surrogates. Crystallographically and spectroscopically, the nature of vitrified glassy slag has been confirmed. Dispersive metal-bearing second phases were found embedded within the matrix of vitrified glassy slag, indicative of a rather uniform mixing molten state occurring during the treatment. Such mixing state was attained primarily by the reshuffling of materials and heat convection in the melt. Formation of metal-bearing phases in the slag was closely related to the metallic waste treated; the increased metallic feed resulted in increases of the second phase formation as well as the slag density. The encapsulation of metal-bearing phases by the slag matrix was found very effective, as indicated by the fairly low leachability characteristics for the elements analyzed. To obtain better leachability results with the INER plasma system, the feed compositions were optimal when the metallic components were kept less than 40 wt.%.

Acknowledgement

The authors gratefully acknowledge the support of the Department of Health of the Republic of China under contract number DOH86-TD-121.

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