1. Introduction

The shredder dust is produced from scrapped automobiles and home electric appliances by shredding and sorting for the purpose of collecting metals, and its amount is about 1.2 million tons a year in Japan. This shredder dust has been conventionally dumped in landfill sites of the stable type. As a countermeasure to the environmental pollution caused in areas that surround the disposal sites, the Waste Disposal and Public Cleansing Law was amended. And it was legislated in April 1996 not to dump the shredder dust but in landfill sites of the control type. Presumably, however, the shortage of landfill sites of the control type will bring in such social problems as the increase of the treatment cost and illegal dumping of the shredder dust. So it is necessary to establish some appropriate treatment technology capable of reducing the volume of the shredder dust, making the dust harmless and reusable, as soon as possible.

Though the shredder dust contains much incombustible matter and has many toxic ingredients such as heavy metals, it cannot be sufficiently reduced in its volume and made harmless by the treatment by using the conventional incineration technology. In order to solve this problem, the authors suggested the method to treat the shredder dust by the direct melting process of the coke-bed type shaft furnace. The treatment of municipal solid waste (MSW) by the process has been proven to be effective in many commercial plants. In this study, the characteristics of the shredder dust compared with those of MSW were investigated. Some experiments on melting treatment of the shredder dust were carried out at the direct melting experimental plant. As a result, the shredder dust was efficiently and stably treated by using the direct melting technology which utilized a multi-stage blasting. Also the content of dioxins in the exhaust gas was below 0.1 ng-TEQ/Nm³ and the gas was purified with the conventional pollution control technology. The slag and metal produced from the shredder dust were reusable in the same way as those from MSW and the volume reduction of the waste was remarkably realized by the application of the direct melting technology.

KEY WORDS: waste; shredder dust; melting technology; recycling; slag; metal; exhaust gas.

2. Characteristics of Shredder Dust

2.1. Properties

The shredder dust contains a large amount of incombustibles and some toxic ingredients. Therefore, the shredder dust is very difficult to be reduced in its volume and made harmless in the treatment by using the conventional incineration technology. In order to solve this problem, the authors suggested the method to treat the shredder dust by the direct melting process of the coke-bed type shaft furnace. The treatment of municipal solid waste (MSW) by the process has been proven to be effective in many commercial plants. In this study, the characteristics of the shredder dust compared with those of MSW were investigated. Some experiments on melting treatment of the shredder dust were carried out at the direct melting experimental plant. As a result, the shredder dust was efficiently and stably treated by using the direct melting technology which utilized a multi-stage blasting. Also the content of dioxins in the exhaust gas was below 0.1 ng-TEQ/Nm³ and the gas was purified with the conventional pollution control technology. The slag and metal produced from the shredder dust were reusable in the same way as those from MSW and the volume reduction of the waste was remarkably realized by the application of the direct melting technology.

KEY WORDS: waste; shredder dust; melting technology; recycling; slag; metal; exhaust gas.
2.2. Pyrolysis Characteristics

In order to investigate the pyrolysis characteristics of the shredder dust, some experiments were carried out. Figure 3 shows an outline of the experimental apparatus. The apparatus consists of a rectangular pyrolysis furnace (18 mmW x 98 mmL x 175 mmH) and a tar pot etc. for catching the products from the reaction. An 80 g sample was used for the experiment. The sample was crushed to a grain averaging 0.66 mm.

In the experiment, the temperature was raised from the room temperature to 1000°C at a rate of 3°C/min in an argon atmosphere. Tar, light oil, pyrolysis gas, water and residue generated by the reaction were collected, weighed and analyzed.

Figure 4 compares the composition of pyrolysis products from the shredder dust with that from MSW. The shredder disposed in high concentration.

| Main 3 components (wet%) | MSW (n=2) | Shredder dust (n=6) |
|-------------------------|-----------|---------------------|
| Moisture                | 38.4      | 10.7                |
| Combustible             | 49.8      | 51.1                |
| Ash                     | 11.8      | 38.2                |

| Kind composition (dry%) |     |       |
|-------------------------|-----|-------|
| Paper                   | 40.8| 2.9   |
| Fiber                   | 7.2 | 7.4   |
| Plastic                 | 19.1| 56.4  |
| Rubber, Leather         | 6.0 | 6.2   |
| Wood, Straw             | 9.1 | 0.7   |
| Rubbish                 | 9.9 | 0.0   |
| Metal                   | 3.0 | 7.0   |
| Glass, Ceramic          | 6.8 | 1.5   |
| Miscellaneous           | 4.1 | 23.9  |

Lower calorific value (MJ/kg) | 9.08 | 15.91 |

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\text{Cu (wet%) = 0.02}, \quad \text{Pb (wet%) = 0.037}, \quad \text{Cd (wet%) = 0.63}
\]

Fig. 1. Flow diagram of direct melting process for recycling municipal solid waste.

Fig. 2. Appearance of shredder dust.

Fig. 3. Schematic diagram of experimental apparatus for pyrolysis characteristics.

Fig. 4. Comparison of composition of pyrolysis products from the shredder dust with that from MSW.
dust is low in moisture and pyrolysis residue and tar-plus-light oil occupy a large ratio of total products. As shown in Fig. 5, the carbon content in pyrolysis residue was similar to that of MSW, although the carbon content in the shredder dust is higher than that of MSW. Thus it is estimated that the amount of the carbon in the pyrolysis residue of the shredder dust capable of contributing to the combustion heat source in the furnace was nearly the same as that of MSW.

2.3. Change of the Layer Thickness in the Pyrolysis Process

Because the shredder dust contains many kinds of plastics and so on, it was expected that the layer thickness reduction of the shredder dust might be greater than that of MSW in the pyrolysis reaction. Therefore by using X-ray scanner with an oven, the change of the layer thickness in the pyrolysis process was directly observed.

Figure 6 shows the schematic diagram of X-ray scanner with the oven, which includes X-ray CT scanner and the oven (50 mmW × 69 mmL × 150 mmH). The oven was filled with 145 g waste averaging 0.66 mm grain and temperature was raised from the room temperature to 850°C at a rate of 10°C/min in an argon atmosphere, and the pyrolysis process of waste was directly observed.

Figure 7 shows the results of direct observation of the pyrolysis of the shredder dust and MSW. The changes of the layer thickness are indicated in Fig. 8. There was no remarkable difference between the two cases from the room temperature to approximately 350°C, but the reductions of

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**Fig. 4.** Composition of pyrolysis products.

**Fig. 5.** Carbon content in pyrolysis products (based in wet).

**Fig. 6.** Schematic diagram of experimental apparatus for direct observation in the pyrolysis process.

**Fig. 7.** Direct observation in the pyrolysis process by X-ray scanner.

**Fig. 8.** Change of layer thickness in the pyrolysis process.
the layer thickness were greater above 400°C in the case of the shredder dust. At 800°C, the layer thickness of the shredder dust was about 70% of the one before the experiment and about 10% less than that of MSW.

Figure 4 shows that the pyrolysis residue ratios of the shredder dust and MSW are 56% and 24% respectively. Taking into consideration each of relative volumes of post-pyrolysis which can be calculated from Fig. 8 (70% and 80%, respectively), the apparent density of the pyrolysis residue of the shredder dust was approximately double that of MSW. This suggests greater permeability resistance in the melting furnace.

2.4. Permeability Characteristics

In order to estimate the permeability of the shredder dust, an experiment on permeability resistance was conducted. An outline of the experimental apparatus is shown in Fig. 9. The acrylic cylinder (500 mm diameter × 800 mm height) was filled with waste and some air was let in from the bottom. A pressure drop per meter of the packed bed was calculated by measuring the pressure at two points in the cylinder. The waste before the pyrolysis process and the pyrolysis residue were used as samples in this experiment.

Figure 10 shows the relationship between the cross sectional mean velocity in a tube and the pressure drop. Usually, the pressure drop rises as the cross sectional mean velocity increases. In this respect, the shredder dust showed a similar tendency to that of MSW. When compared at the same cross sectional mean velocity, the pressure drop of the original shredder dust was approximately 0.5 kPa higher than that of MSW. The pressure drop of the pyrolysis residue of the shredder dust was approximately double that of MSW. Taking the result of Sec. 2.3 into consideration, the permeability resistance of the shredder dust in the melting furnace is expected to increase.

3. Outline of the Direct Melting Experimental Plant and Experimental Method

3.1. Outline of the Direct Melting Experimental Plant

The equipment flowsheet of the experimental plant is shown in Fig. 11. The waste treatment capacity of this plant is 10 tons per day. The plant consists of a direct melting furnace (the diameter of a shaft being 1 m and 4 m high), a combustion chamber, equipment for gas treatment and lastly recycling equipment for molten matter.

The direct melting furnace is schematically shown in Fig. 12. The melting furnace itself used for this process is a shaft furnace. Waste, coke and limestone are charged into the central top of the furnace and in the furnace the packed bed is formed by the wastes and these auxiliary materials. The furnace is divided into three zones from the top to the bottom, namely the drying and preheating zone which is about 300°C, the thermal decomposition zone being 300–1000°C and the combustion and melting zone which is 1700–1800°C. In the drying and preheating zone, the waste charged is dried on heating. The dried waste gradually descends into the thermal decomposition zone where organic substances are gasified. The gases produced in this way are discharged from the furnace top and completely burnt in the subsequent combustion chamber.

The melting furnace is equipped with lower and upper blasting near the bottom. In other words, the furnace is of a multi-stage blasting type. Some air at ordinary temperature is injected through the upper tuyeres for effectively burning the carbon in the waste. Air enriched with oxygen at ordinary temperature is injected through the lower tuyeres to burn the coke, thus forming a coke bed with high temperature in the lower part of the furnace. This heat is used to melt incombustibles and inorganic substances completely. The hot molten matter, adjusted in its basicity and viscosity by CaO which is contained in the limestone, is discharged from the furnace through the tap hole. The molten matter is sent into the granulating equipment, where it is rapidly cooled and solidified into granular mixture of slag and metal. The granular mixture is separated into slag and metal by magnetic separator for recycling.

The direct melting technology has been developed for the treatment of MSW and the maximum capacity of commercial plants is 150 t/day.

3.2. Experimental Methods and Conditions

The shredder dust was directly charged into the furnace without any pretreatment in the same way as in commercial practice. The experimental results of the shredder dust were evaluated in comparison with those of MSW.
Based on the characteristics of the shredder dust, as mentioned in Chap. 2, the experimental conditions of melting treatment of the shredder dust were as follows.

1. As the shredder dust contains a large amount of incombustibles (ash) compared with MSW, it is necessary to secure sufficient melting heat, by effectively utilizing combustible matters in the shredder dust. In other words, in order to promote the combustion of the carbon in the shredder dust, a multi-stage blasting type (upper tuyere oxygen ratio: 50%–60%) was adopted. Furthermore, the coke rate of 60 kg/t was adopted in the same way as that of MSW treatment.

2. The ash content in the shredder dust being high, the limestone rate was increased to maintain the slag basicity within the ranges of 0.7–1.0 in order to ensure the fluidity of molten matter.

3. As the shredder dust has high permeability resistance, it is necessary to adjust the height of packed bed and gas flow rate in the furnace. On the other hand, the shredder dust has less moisture than MSW, so the drying and preheating zone of the shredder dust is shorter in its width than that of MSW. Therefore, when permeability varied during melting, it was adjusted by reducing the height of packed bed in the furnace.

Several kinds of waste such as \(\text{\% MSW alone,} \quad 50\%\text{ MSW and the shredder dust respectively and} \quad 100\%\text{ shredder dust alone,} \) were used in the melting experiments. In the case of the shredder dust and MSW were charged into the furnace alternately.

4. Experimental Results and Discussion

4.1. Experiment of Melting Treatment

The three experimental results concerning the treatment of 100% MSW alone, 50% MSW and the shredder dust respectively and 100% shredder dust alone are shown in Table 2. The blast volume was set low at around 450 Nm\(^3\)/h, for the adjustment of the exhaust gas volume in the treatment of the shredder dust. When the ratio of the shredder dust to MSW increased, the limestone rate increased by...

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**Fig. 11.** Flow diagram of direct melting experimental plant.

**Fig. 12.** Direct melting furnace.
30–60 kg/t more than that of MSW. The data of the treatments of the shredder dust were average values during two days, while other data being those during a day.

It was confirmed that a stable treatment could be achieved with 50% MSW and the shredder dust respectively under the operational conditions of the coke rate of 60 kg/t and the oxygen content of 25% with the multi-stage blasting type. And in the operational case of 100% shredder dust, it was confirmed that a stable treatment could be achieved in the same way as the treatment of MSW. The rate of the melting treatment of 50% MSW and the shredder dust respectively was about 12 t/d, while that of 100% shredder dust being about 12 t/d. The molten matter ratio (a weight of molten matter discharged per ton of waste) increased as the shredder dust ratio increased. This fact clearly showed that the amount of residue melted in the melting furnace increased as the ash content of waste increased. Also permeability (pressure in the furnace) could be maintained at approximately the same level as that of MSW. The height of the packed bed in the furnace was 80% of that of MSW.

Figure 13 shows the temperature distribution of the molten matter in melting treatment of shredder dust.

Table 2. Operating results of melting treatment.

|                         | MSW | Shredder dust 50% | Shredder dust 100% | Shredder dust 100% |
|-------------------------|-----|-------------------|-------------------|-------------------|
| Melting treatment rate  | (kg/h) | 615 | 496 | 483 | 500 |
| Molten matter rate      | (kg/t) | 176 | 284 | 406 | 336 |
| Molten matter temperature | (°C) | 1481 | 1504 | 1525 | 1535 |
| Pressure in the lower part of furnace | (kPa) | 1.35 | 1.34 | 2.17 | 1.50 |
| Coke rate               | (kg/t) | 60 | 61 | 60 | 61 |
| Line stone rate         | (kg/t) | 80 | 116 | 138 | 128 |
| Blast volume            | (Nm³/h) | 525 | 526 | 447 | 474 |
| Oxygen content in blast | (%) | 25 | 25 | 26 | 26 |

Fig. 14. Form of carbon consumption in melting furnace.

Fig. 15. Heat balance of shredder dust operation compared with MSW operation.

and the carbon contained in the waste is gradually decomposed and gasified as the temperature of the waste rises. In the lower part of the furnace of a high temperature, carbon is consumed by the reaction of combustion caused by the oxygen of a blast into the furnace and the reaction of solution loss. For the purpose of understanding these carbon behaviors quantitatively, a model4) for the mass balance was utilized. This model is calculated from the compositions of top gas etc. generated from the furnace.

The forms of the carbon consumption in the furnace are indicated in Fig. 14. The amount of the shredder dust carbon contributing to combustion in the furnace was nearly the same as that of MSW. But the amount of the carbon in pyrolysis gas etc. generated from the shredder dust was higher. This result was the same as the findings of the characteristics of both the wastes.

Figure 15 shows the results of the heat balance which was calculated on the basis of Fig. 14. The energy of the input heat obtained by the combustion of coke and waste was nearly the same in both of the wastes. In the melting treatment of the shredder dust, the sensible heat necessary for melting increased in accordance with the increase of ash content. And the heat necessary for drying decreased in accordance with the decrease of water content. The quantity
of the increase of the sensible melting heat was equivalent to the quantity of the decrease of the drying heat. This result suggests that the shredder dust can be efficiently and stably treated.

In the treatment of 50% MSW and the shredder dust respectively and the 100% shredder dust, stable operations were verified by applying the multi-stage blasting type as in the case of MSW treatment. These results of the experiment suggest that the direct melting treatment of the shredder dust is fully possible on a commercial plant scale because this technology has a capacity to treat 150 t/d MSW.

4.2. Exhaust Gas Treatment

Table 3 shows the results of exhaust gas analysis. O₂ and CO levels in emission gases and the temperature of an exit of the combustion chamber are averages of the data collected during the period. Other values are of the batch analysis results. The values gained from gas analysis are of 12% O₂ equivalents. The figures in the parentheses show the measurements in the stack.

The outlet temperature of the combustion chamber during the melting treatment of the shredder dust was maintained at about 850°C. It was confirmed that the exhaust gas could be treated with the conventional technology of pollution control that has been used for MSW treatment, though the HCl content in the shredder dust operation was higher than that of MSW. The technology is like the injection of slaked lime and ammonia. The content of dioxins of the exhaust gas was below 0.1 ng-TEQ/Nm³ of the latest guideline of dioxins directed by the Ministry of Welfare. The fact means that in this process the efficiency of the waste gasification is so high that the formation of the dioxins is suppressed by complete gas burning in the independent combustion chamber.

4.3. Properties of Molten Matter

Tables 4 and 5 show the chemical composition of slag and the test result of slag leaching. The properties of molten slag from the shredder dust were nearly the same as those of MSW treatment, and the lead content was very low, that was about 20 ppm. Also, the leaching values of heavy metals were all below the limit values of the environmental standard for soil. In this process coke and limestone are charged into the melting furnace with the waste for the purpose of high temperature melting and the adjustment of basicity. And a reducing atmosphere under high temperature is serviceable to facilitate the volatilization of alkali salts and heavy metals contained in the waste, and the atmosphere suppresses the invasion of heavy metals into the slag. Therefore the slag is harmless.

A test of asphalt mixture was conducted in order to evaluate the effective utilization of slag from the shredder dust. Table 6 shows the results of a comparative test regarding an ordinary asphalt mixture using 100% natural sand and the one using 10% slag. The slag from the shredder dust showed nearly the same of the characteristic value of the Marshall test as the ordinary natural sand. Thus the outlook was favorable for using the slag produced from the shredder dust as a fine aggregate for a mixture with asphalt.

Table 7 shows the chemical composition of metal. The characteristic point of the metal produced from the shredder
dust was its high copper content compared with the metal from MSW and thus this metal is possible to be used as counterweights for construction machinery.

The above experimental results clarified that the molten matter produced during melting treatment of the shredder dust was harmless and reusable. Only the 30 kg/t fly ash which contains injected slaked lime and is mainly collected in the dust collector, requires final disposal. Table 8 shows the chemical composition of fly ash without any slaked lime injection. Compared with MSW, Zn and Pb increased in the shredder dust fly ash. Especially some 90% of the Pb originally contained in the shredder dust was transferred to the fly ash. This phenomenon was caused by the accelerated volatilization of Pb in a reducing atmosphere of high temperature. The reduction ratio of volume calculated from the experimental result is about 1/200 of the volume of the shredder dust before the melting treatment.

5. Conclusion

As a new process for treating the shredder dust, the direct melting process in coke-bed type shaft furnace was proposed. The characteristics of the shredder dust were investigated and a study of the experimental plant was carried out. The results were as follows;

(1) The shredder dust is high in ash content and low in moisture. Carbon content in pyrolysis residue of the shredder dust is similar to that of MSW. According to the change of layer thickness in the pyrolysis process and also according to the permeability, the shredder dust showed a tendency to increase in permeability resistance. In view of these characteristics of the shredder dust, a multi-stage blasting type was adopted as the most suitable operation method. The appropriate coke rate, limestone rate and the height of the packed bed in the furnace were adopted.

(2) According to these results, it was verified that the shredder dust as well as in the case of MSW could be efficiently and stably treated by using the direct melting technology which utilized a multi-stage blasting.

(3) It was confirmed that the exhaust gas can be treated with the conventional pollution control technology used in MSW treatment. Slag and metal from the shredder dust were reusable in the same way as those from MSW and much reduction of the volume of waste was realized by applying the direct melting technology.

The remaining capacity of final disposal sites for the industrial waste are decreasing, and new sites are more difficult to be secured. Against such a background, there is further demand for methods of treating and recycling waste appropriately, which is difficult to treat with conventional techniques. The authors would like to study the broadening of the applications of the direct melting process so as to meet this demand.

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