Journal of Hazardous Materials 161 (2009) 775–780

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Novel method to evaluate the net wear volume of bag-filter by fly ash

Yoshimi Watanabe [a,b,*], Hisashi Sato [a], Yu Hirai [b], Ick-Soo Kim [b], Shigeru Hinata [b], Jooyong Kim [c]

[a] Omohi College, Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
[b] Depertment of Functional Machinery and Mechanics, Shinshu University, 3-15-1 Tokida, Ueda 386-8567, Japan
[c] Textile Engineering, Soongsil University, 511 Sangdo-Dong, Dongjak, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 7 February 2008
Received in revised form 8 April 2008
Accepted 8 April 2008
Available online 14 April 2008

Keywords:
Wear
Saturation magnetization
Magnetic material
Bag-filter
Shot peening

ABSTRACT

In order to study the wear of bag-filter by ash dust, sintered magnetite (Fe_3O_4) compact was used for counter material for sliding wear test. The precise amount of magnetite particles embedded into bag-filter was determined by a vibration sample magnetometer (VSM) measurement. It is found that net amount of wear of the bag-filter could be precisely determined by the magnetic measurement. It is also found that the net amount of sliding wear of the bag-filter increases with increasing the wear distance, sliding speed and applied load. To discuss the validity of proposed method, shot peening test with deoxidized iron particles was also carried out for bag-filter sample. The data obtained by the shot peening test is consistent with that obtained by the sliding wear test. The proposed method is, thus, very useful to evaluate the net amount of wear of bag-filter by the fly ash.

1. Introduction

Polychlorinated dibenzo-*p*-dioxins, polychlorinated dibenzofurans and coplanar polychlorinated biphenyls are known to be chemically and biologically similar compounds. They are called as “Dioxins”, and they are highly toxic chemicals [1]. Dioxins tend to enrich on fly ash by the presence of unburned carbon, which adsorbs dioxins. The unburned carbon is a catalyst for dioxin formation in the incineration process [2]. In recent years, with the increase of awareness regarding environmental issues, dioxins have been identified as a major concern relating to health problems. In Japan, the major source of dioxins is incinerators, since most solid waste is incinerated in municipal waste incinerators without sufficient measures to prevent the generation of these chemicals [1]. Fig. 1 shows a flow diagram of typical incineration process. The collected waste is put into the waste pit, and then, is transported into the incinerator by the crane. The waste is burned in the incinerator, while waste is conveyed to the bottom by the stoker. The combustion gas is passed through the cooling tower and bag-filter, and then it is emitted from the chimney, where the bag-filter is in general frequently used for dust removal in industrial applications. The dioxins, as well as fly ash, are normally captured on the internal surface of the bag-filter. Bag-filter could clear ash dust and microscopic particles of deleterious material by passing exhaust gas through a fabric that was treated with a special coat.

However, accidents sometime occur, namely, the bag-filter failed by being worn out due to flying ash dust. Since a reliable method for prediction of the lifetime of those bag-filters was needed, wear mechanism of bag-filter should be known. Wear of the bag-filter should be caused by collision of the ash dust. However, the wear mechanism of the bag-filter by the ash dust is still unclear.

Many methods for measuring the wear properties of textile fabrics and organic and inorganic fibers have been developed [3–5]. For example, tribological investigation of textile fabrics has been carried out by Bueno et al. [3]. On the other hand, an abrasive wear of textile fabric with emery paper has also been studied [4]. Cayer-Barrioz et al. have studied the abrasive wear of polyamide fiber, and they concluded that the abrasive process is responsible for a continuous diminution of the fiber cross-section until the creep failure stress is achieved locally [5]. However, a few studies present the wear behavior of bag-filter by ash dust. One of the main difficulties when studying the wear behavior of bag-filter by ash dust is that the dust ash is embedded into the bag-filter during the wear test. Therefore, there is a need to develop a new technique to evaluate the net amount of wear on the bag-filter.

Meanwhile, magnetic properties of magnetic materials are proportional to its weight. In other words, if magnetic measurement of the magnetic material is performed, the weight of the magnetic material can be calculated. Using this phenomenon, net amount

* Corresponding author at: Omohi College, Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan. Fax: +81 52 735 5624.
E-mail address: yoshimi@nitech.ac.jp (Y. Watanabe).

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doi:10.1016/j.jhazmat.2008.04.024

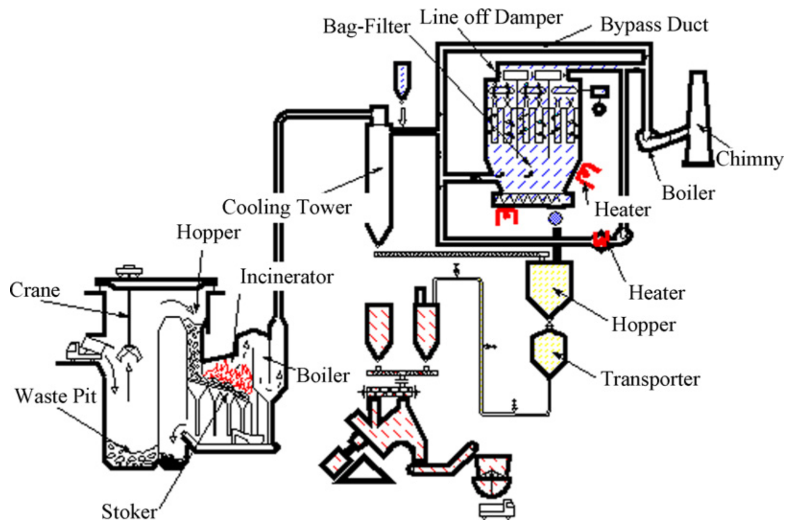

Fig. 1. A schematic illustration showing typical incineration process.

of wear of bag-filter could be precisely evaluated by the magnetic measurement, when the magnetic particles were used as a model of fly ash.

In this study, sintered magnetite compact was used to simulate the ash dust. Wear tests of bag-filter by sintered magnetite compact were performed in different wear conditions. The precise amount of magnetite particles embedded into bag-filter was determined by a vibration sample magnetometer (VSM) measurement. Net wear amount of the bag-filter could be precisely determined by the magnetic measurement. To discuss the validity of proposed method, shot peening tests with deoxidized iron particles were also carried out for bag-filter sample.

2. Theory

In our effort to establish a simple but useful and robust procedure to determine the net wear volume of bag-filter by fly ash, removal of embedded fly ash into the bag-filter is considered. It is well known that saturation magnetization of magnetic materials is proportional to the weight of the magnetic materials. Therefore, the amount of magnetic material-particles embedded into bag-filter could be determined by magnetic measurement; M_m (emu)/I_s (emu/g), where I_s (emu/g) is saturation magnetization of magnetic material-particles and M_m (emu) is measured magnetization. Then, net weight loss due to wear on the bag-filter, ΔM (g), can be evaluated by the following equation.

$$\Delta M(\text{g}) = M_0(\text{g}) - \left[M_\text{w}(\text{g}) - \left\{ \frac{M_\text{m}(\text{emu})}{I_\text{s}(\text{emu/g})} \right\} \right], \quad (1)$$

where M_0 (g) and M_w (g) are the weights of the bag-filter before and after wear test, respectively.

3. Experimental procedures

3.1. Preparation of sintered magnetite compact

Fe_3O_4 (magnetite) particles were used in this study as a magnetic material to simulate the fly ash. The saturation magnetization of magnetite is 92 emu/g at 293 K [6]. The magnetite particles were poured into a mold, and they were compressed under a uniaxial pressure of 19.6 MPa for 120 s in order to obtain rod of 10 mm in diameter. The green body rod height is about 15 mm. Then the magnetite green body was sintered at different temperatures (from 100 to 900 °C every 200 °C) and different periods (1 or 2 h) with a muffle-oven.

3.2. Bag-filter

There are many kinds of materials used for bag-filters. In this study, polyimide bag-filter was used. Fig. 2 shows a microstructure image of polyimide bag-filter observed with a scanning electron microscope (SEM). As can be seen, the polyimide fiber has noncircular cross-section.

3.3. Wear test

Sliding wear tests were performed with a rod-on-disc type wear machine as shown in Fig. 3. Steel disc was covered by a round shaped bag-filter with 110 mm in diameter. The counter sample is a sintered magnetite compact rod. In this study, the applied loads are 30, 50 and 70 g. The relative sliding speeds are 0.25, 0.5 and 0.75 m/s. After the wear test, the bag-filter was cut out 12 mm in diameter, and saturation magnetization of the bag-filter after wear test was measured by a VSM. The weight of magnetite particles embedded into the bag-filter was evaluated from the value of saturation magnetization, and the net weight loss of the bag-filter by

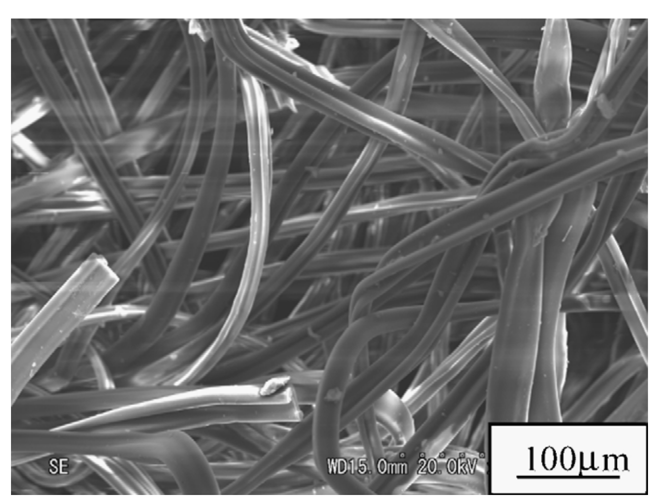

Fig. 2. An SEM micrograph of polyimide bag-filter.

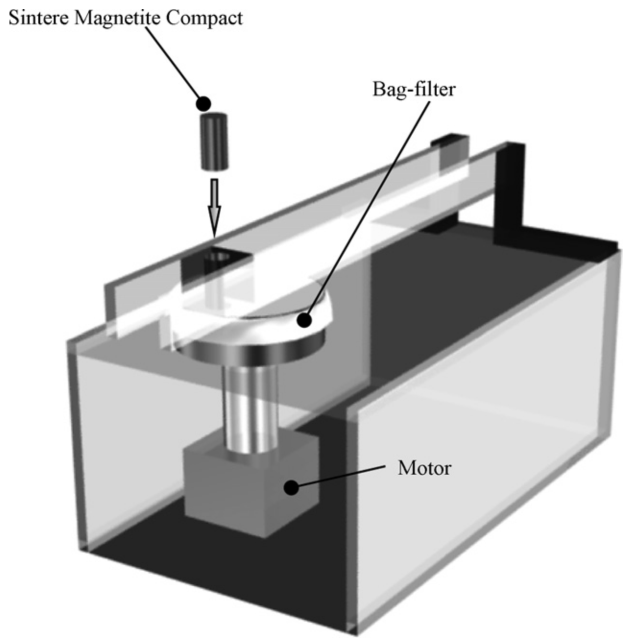

Fig. 3. A rod-on-disc type wear machine.

the wear test was calculated. The worn surfaces were examined using SEM.

4. Results and discussion

4.1. Properties of sintered magnetite compact

Fig. 4 shows the variation of the saturation magnetization of magnetite compacts sintered in air as a function of sintering temperature. It can be seen that as sintering temperature increases the saturation magnetization of sample decreases. There are various iron oxides, *e.g.*, α-Fe_2O_3 (haematite), γ-Fe_2O_3 (maghemite), Fe_3O_4 (magnetite) and $Fe_{1-x}O$ (wustite). It is well known that magnetite and maghemite are ferrimagnetic substances, while haematite and wustite are so-called non-magnetic substances. It is also well known that different iron-oxides can be transformed into others by reduction or oxidation reactions [7–9]. Therefore, the observed variation in the saturation magnetization is likely to be due to phase transformation of magnetite into non-magnetic phase during the sintering in air. To analyze the structural changes during the sintering, X-ray diffraction (XRD) analysis was carried out on a monochrometer-attached diffractometer with radiation from a Cu Kα (λ = 0.15405 nm) source.

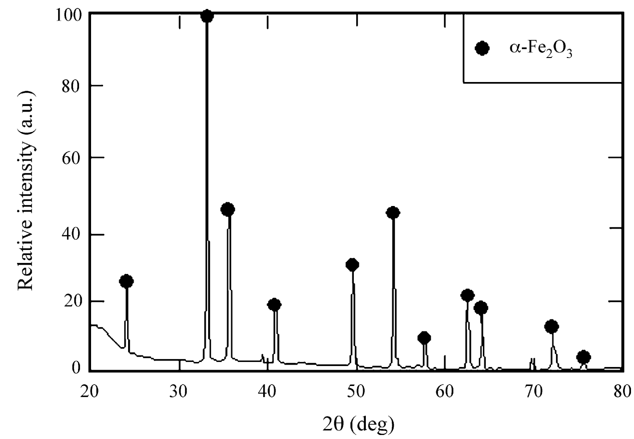

Fig. 5. XRD pattern of the sintered magnetite compact (900 °C, 2 h). Sintering was carried out in the air.

Fig. 5 shows XRD pattern of magnetite compact sintered at 900 °C for 2 h in air. It should be noted that the α-Fe_2O_3 phase was detected after the sintering at 900 °C for 2 h in air. In this way, magnetite is transformed into non-magnetic α-Fe_2O_3 by the sintering in air. Therefore, phase transformation (oxidation) during the sintering must be prevented.

Next sintering was carried out in vacuum condition to avoid the phase transformation (oxidation). Fig. 6 is a plot of the saturation magnetization of sintered magnetite compact, which was sintered in vacuum condition, as a function of sintering temperature. One may have noticed that magnetite compacts sintered in vacuum keep in the saturation magnetization as the sintering temperature increases. Thus, sintering of magnetite should be carried out in vacuum.

To study the wear resistance of sintered magnetite compact, the wear amount of magnetite compact sintered in vacuum condition was measured, and results are shown in Fig. 7. In this case, buff was used for the counter surface. As shown in Fig. 7, the wear amount of sintered magnetite compact was reduced with increase in sintering temperature. Moreover, higher wear resistance is found for the

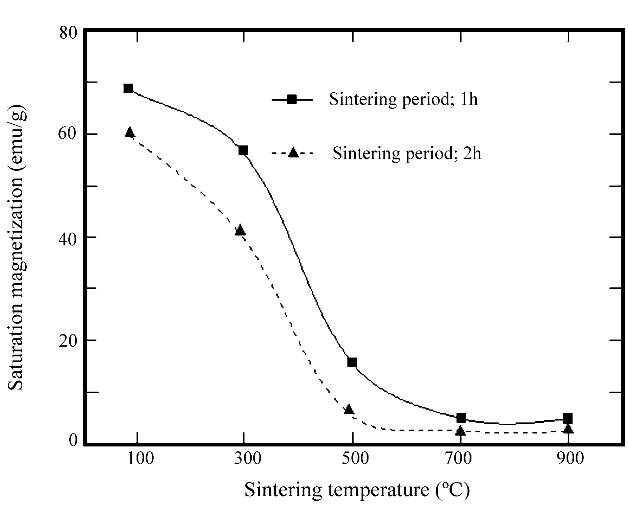

Fig. 4. Saturation magnetization of magnetite compact sintered in air.

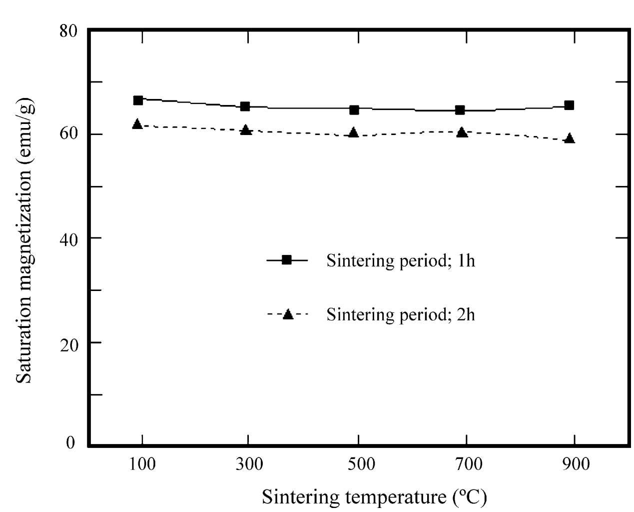

Fig. 6. Saturation magnetization of magnetite compact sintered in vacuum.

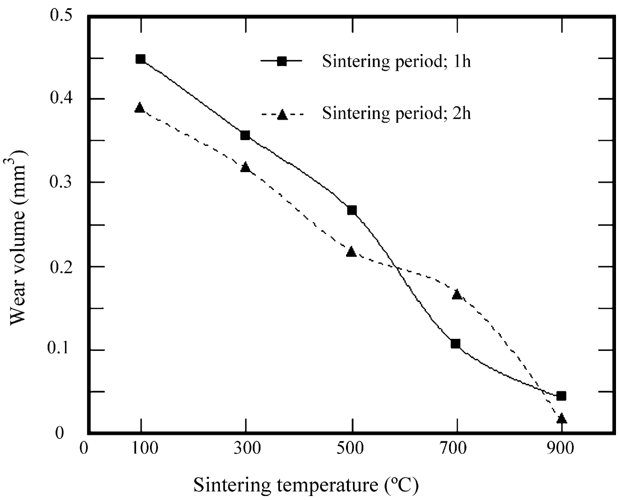

Fig. 7. Wear volume of magnetite compact sintered in vacuum. Counter surface is buff.

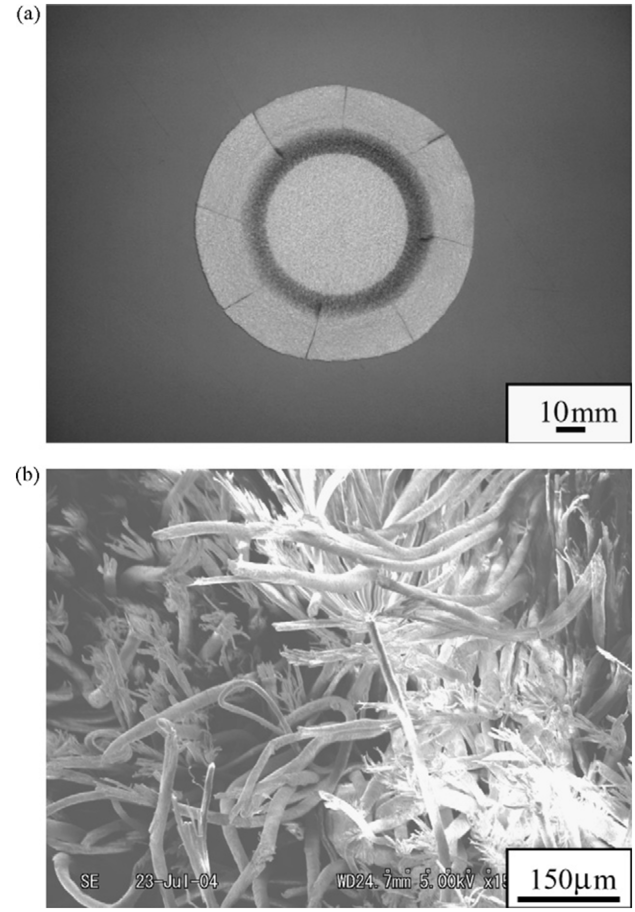

Fig. 8. (a) Macroscopic and (b) microscopic images of the bag-filter after wear test.

samples sintered for longer sintering period. Therefore, the optimized sintering condition is that; sintering in vacuum condition at high sintering temperature (900 °C) and longer sintering period (2 h). The following wear tests for bag-filter, sintered magnetite compacts sintered by optimized sintering condition were used as the counter surface.

4.2. *Wear of bag-filter by sintered magnetite compact*

Wear tests of bag-filter by sintered magnetite compact was carried out under varying conditions. Fig. 8 gives an example of the bag-filter after wear test. Macroscopic and microscopic images are shown in Figs. 8(a) and (b), respectively. It is clear from Fig. 8(a) that the magnetite particles are embedded into the bag-filter. As shown in Fig. 8(b), breaking of the polyimide fiber by wear was observed.

It is known that a large plastic strain near a worn surface is produced by sliding wear, especially in unlubricated states [10,11]. It has been reported that a phase transformation from α-Fe_2O_3 (antiferromagnetic) to γ-Fe_2O_3 (ferrimagnetic) was induced by a simple grinding test [12]. Therefore, magnetite can be transformed into other oxides during the wear test. Although the data is not presented here, only magnetite was detected and no other phases such as α-Fe_2O_3 (haematite) or γ-Fe_2O_3 (maghemite) were found for XRD pattern of the sintered magnetite compact after the wear test. Therefore, the amount of embedded particles can be safely evaluated from Eq. (1).

Fig. 9 shows the net wear amount of bag-filter with a change of the wear distance. Sliding speed and applied load were 0.25 m/s and 70 g, respectively. Data points with error bars are experimental means and standard deviations of a minimum five specimens. As can be seen from Fig. 9, the wear amount of the bag-filter increases with increasing the wear distance. It is worthwhile to note that a linear relationship between the wear amount of bag-filter and the wear distance was found.

Fig. 10 shows the wear amount of bag-filter as a function of the sliding speed. Wear distance and applied load were 150 m and 70 g, respectively. From this figure, the wear volume of bag-filter was increased as the sliding speed increased. In general, it is known that the coefficient of dynamic friction is reduced as the sliding speed increases. Although the dynamic friction was not measured during the wear test, the dynamic friction may affect the amount of wear of bag-filter.

The effect of applied load on the amount of wear is shown in Fig. 11. Wear distance was 75 m and sliding speed was 0.25 m/s. It is found that the relationship between the wear amount of bag-filter and the applied load is almost linear.

4.3. *Validity of proposed method*

In this study, a novel method to evaluate the net wear volume of bag-filter by ash dust is proposed. The study allows us to predict the net wear amount of the bag-filter against sintered magnetite com-

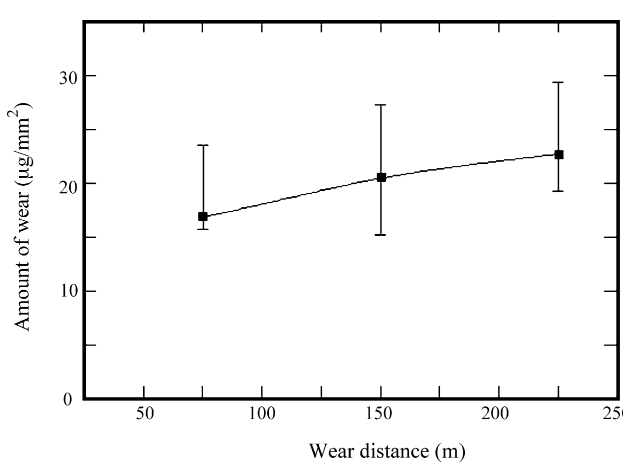

Fig. 9. The net amount of wear of bag-filter with a change of the wear distance.

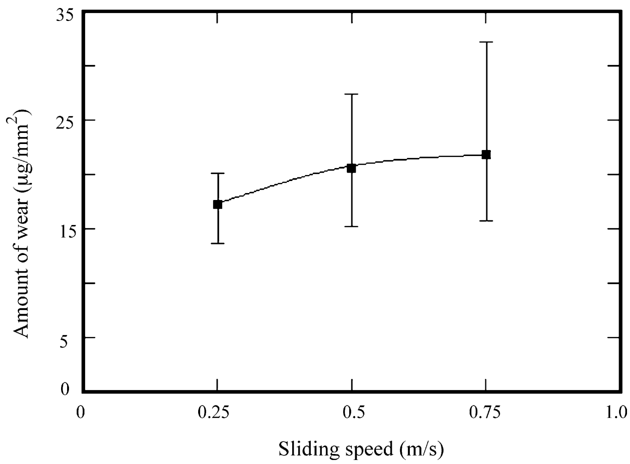

Fig. 10. The net amount of wear of bag-filter with a change of the sliding speed.

pact by the magnetic measurement. Of course, the wear behavior of the bag-filter is strongly influenced by the mechanical properties of the sintered magnetite compact. Therefore, an understanding of the mechanical-property difference among sintered iron, typical fly ash compositions and unburned carbon particles is of scientific interest as well as technological importance. However, it is difficult to discuss the mechanical-property difference among sintered iron, typical fly ash compositions and unburned carbon particles although this would be expected to control wear rates.

Alternatively, shot peening tests for bag-filter were carried out [13], where the shot peening is known to be the most widely used method to improve the strength of metal components. It consists of projecting small shots made of steel, ceramic or glass, at relatively high velocities (20–100 m/s) at the surfaces of the metallic parts [14]. Recently, Umemoto et al. found that a nano-crystalline structure can be produced by severe plastic deformation introduced by the shot peening [15]. Therefore, an accelerated wear test could be carried out by the shot peening test, where the wear of the bag-filter by the shot peening test is resemble those caused in the incinerator.

The polyimide sample used for shot peening test was cut into a 110 mm diameter disc. Shot peening test was conducted by a flow of deoxidized iron particles with a diameter of 100–125 μm at 0.2, 0.3 and 0.4 MPa. The wear duration was in the range from 30 to 120 s. The deoxidized iron shot is accelerated in the nozzle to a high velocity and hits the bag-filter's surface. The shot peening process is

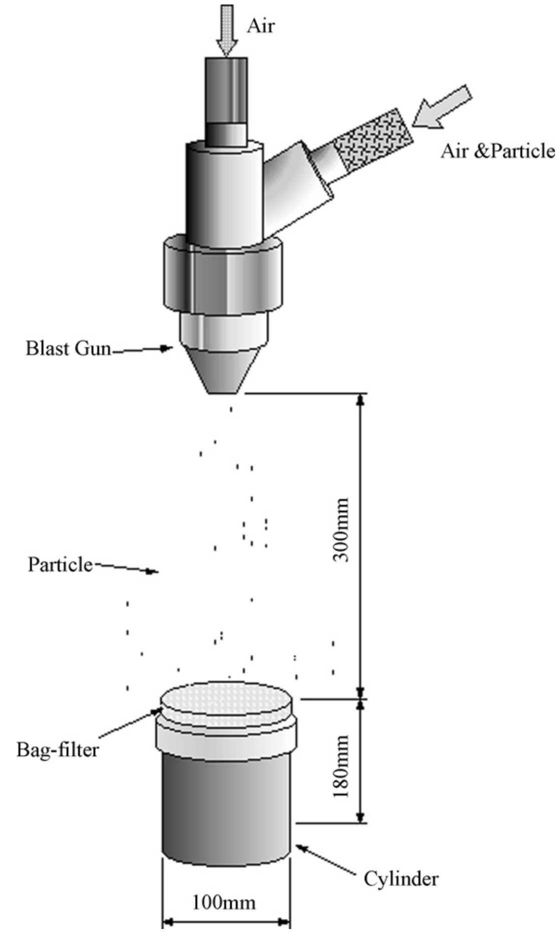

Fig. 12. A schematic presentation of the shot peening process used in this study.

illustrated in Fig. 12. The most important shot peening parameters are indicated in the figures. After the wear by shot peening test, saturation magnetization of the peened samples was measured by the VSM.

Fig. 13 shows the net wear amount of bag-filter by shot peening test with a change of the injection time. It can be seen that the amount of wear of the bag-filter increases with increasing the injection time. Moreover, the larger amount of wear was observed for larger injection pressure. These results are consistent with the data obtained by the sliding wear test using the sintered magnetite.

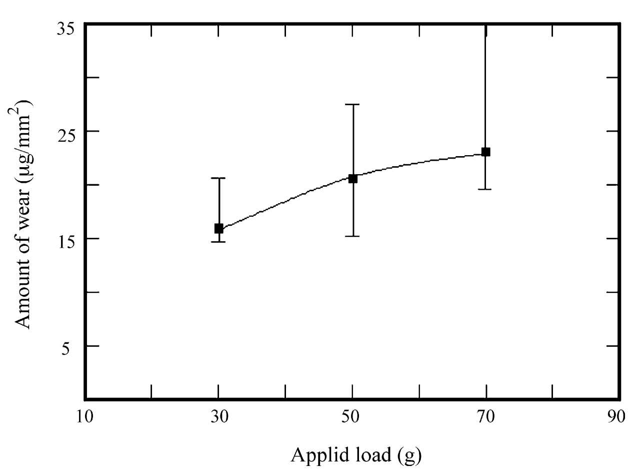

Fig. 11. The net amount of wear of bag-filter with a change in the applied load.

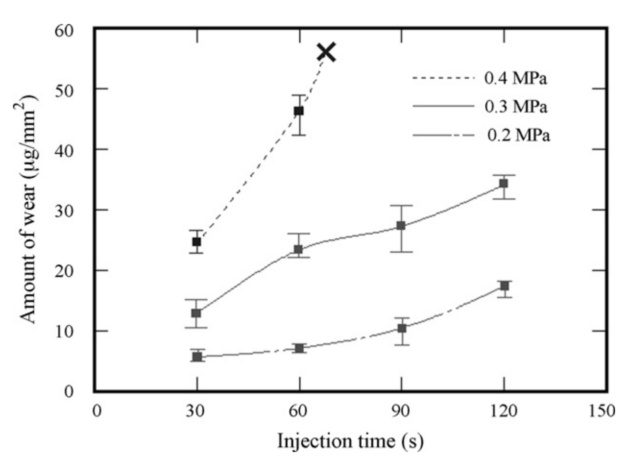

Fig. 13. The net amount of wear of bag-filter by shot peening test.

Therefore, we can conclude that the proposed method is very useful to evaluate the net amount of wear of bag-filter by the ash.

5. Conclusions

In order to study the wear of bag-filter by ash dust, sintered magnetite compact was used for counter material. The amount of magnetite particles embedded into bag-filter was determined by magnetic measurement. The obtained results are summarized as follows:

(1) Best sintered magnetite compact was obtained in a vacuum condition at a high sintering temperature (900 °C) and a longer sintering period (2 h).
(2) Net amount of wear of the bag-filter could be precisely determined by the magnetic measurement.
(3) It was found that the net amount of wear of the bag-filter increases with increasing the wear distance, sliding speed and applied load.
(4) The data obtained by the shot peening test is consistent with that obtained by the sliding wear test.
(5) The proposed method is very useful to evaluate the net wear amount of bag-filter by the fly ash.

Acknowledgements

This study is supported by a Grant-in-Aid for Scientific Research B (2) (14350105) and a Grant-in-Aid for Scientific Research on Priority Areas (19025005) by the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] S. Kumagai, S. Koda, T. Miyakita, H. Yamaguchi, K. Katagi, M. Ueno, Estimation of dioxin exposure concentrations and dioxin intakes of workers at continuously burning municipal waste incinerators, J. Occup. Health 43 (2001) 61–69.
[2] A. Shibayama, Y. Kim, S. Harjanto, Y. Sugai, K. Okada, T. Fujit, Remediation of contaminated soil by fly ash containing dioxins from incineration by using flotation, Mater. Trans. 46 (2005) 990–995.
[3] M.-A. Bueno, B. Lamy, M. Renner, P. Viallier-Raynard, Tribological investigation of textile fabrics, Wear 195 (1996) 192–200.
[4] M.-A. Bueno, B. Lamy, M. Renner, Effect of grain size and abrasion duration on the state of textile fabric surfaces, Wear 253 (2002) 448–457.
[5] J. Cayer-Barrioz, D. Mazuyer, P. Kapsa, A. Chateauminois, F. Bouquerel, On the mechanisms of abrasive wear of polyamide fibres, Wear 255 (2003) 751–757.
[6] S. Chikazumi, Physics of Magnetism. Magnetic Properties of Matter, vol. 1, Syokabo, Tokyo, 1978, p. 222.
[7] S. Kachi, K. Momiyama, S. Shimizu, An electron diffraction study and a theory of the transformation from γ-Fe_2O_3 to α-Fe_2O_3, J. Phys. Soc. Jpn. 18 (1963) 106–116.
[8] J.R. Porter, P.R. Swann, High-voltage microscopy of reduction of hematite to magnetite, Ironmak. Steelmak. 4 (1977) 300–307.
[9] Y. Watanabe, K. Ishii, N. Ishikawa, K. Furuya, M. Kato, In-situ observation of transformation in α-Fe_2O_3 under hydrogen implantation, J. Phys. Condens. Matter 14 (2002) 13643–13651.
[10] X.Y. Li, K.N. Tandon, Amorphization and precipitation within the amorphous layer induced by dry sliding wear of an Al–Si/SiCp composite material, Acta Mater. 44 (1996) 3611–3624.
[11] Y. Watanabe, N. Yamanaka, Y. Fukui, Wear behavior of Al–Al_3Ti composite manufactured by a centrifugal method, Metall. Mater. Trans. A 30A (1999) 3253–3261.
[12] S. Meillon, H. Dammak, E. Flavin, H. Pascard, Existence of a direct phase transformation from haematite to maghemite, Philos. Mag. Lett. 72 (1995) 105–110.
[13] Y. Watanabe, S. Kishi, H. Sato, K. Mibu, S. Shimakawa, S. Hinata, Evaluation methods of wear properties of bag-filter using an optical fiber and magnetic particles, Sen-i Gakkaishi 64 (2008) 79–84 (Japanese).
[14] M. Frija, T. Hassine, R. Fathallah, C. Bouraoui, A. Dogui, Finite element modelling of shot peening process: prediction of the compressive residual stresses, the plastic deformations and the surface integrity, Mater. Sci. Eng. A 426 (2006) 173–180.
[15] M. Umemoto, Y. Todaka, K. Tsuchiya, Formation of nanocrystalline structure in steels by air blast shot peening, Mater. Trans. 44 (2003) 1488–1493.