JFE TECHNICAL REPORT
No. 19 (Mar. 2014)

Development of Waste Plastics Pulverization for Blast Furnace Injection†

ASANUMA Minoru[*1] TERADA Kaneo[*2] INOGUCHI Takanori[*3] TAKASHIMA Nobuhiro[*4]

Abstract:

Successful recycling of waste plastics is critical to save natural resources and reduce CO_2 emissions. Since 1996, waste plastics have been utilized in JFE Steel for reducing agent of iron ore by injection into blast furnace. Waste plastics used in the blast furnace are coarse particles, because of the difficulty to crushed into fine particles. Considering the utilization efficiency of waste plastics in the blast furnace, fine particles are better in performance. Therefore, the technology for fine pulverization of waste plastics has been developed. It has been successfully applied in actual blast furnaces, contributing to lowering the reducing agent rate.

1. Introduction

Discharges of waste plastics in Japan are estimated at approximately 10 million tons/year. In 2000, Japan began full enforcement of the Law for Promotion of Sorted Collection and Recycling of Containers and Packaging (hereinafter, the Containers and Packaging Recycling Law), which is applicable to general waste, in order to promote recycling of these waste plastics, and as a result, the recycling ratio of waste plastics has increased steadily (effective utilization was 50% in 2000 and had risen to 78% in 2011)[1)]. At present, the recycling methods which are authorized under the Containers and Packaging Recycling Law are material recycling, that is, recycling as plastic products, and various forms of chemical recycling such as use as blast furnace feed or coke feed, gasification, liquefaction, etc.[1)].

On the other hand, over the last several decades, Japanese steel makers have made efforts to conserve energy and resources and to reduce CO_2 emissions and now boast the lowest unit energy consumption in the manufacture of iron and steel products in the world. However, in order to realize further resource savings and reductions in CO_2 emissions, the Japan Iron and Steel Federation set a target of reducing average energy consumption during the period of 2008–2012 by 10% from the level in 1990 (preconditioned on crude steel production of 100 million tons/year) as a Voluntary Action Plan for prevention of global warming. The industry also foresees additional use of 1 million tons of waste plastics, etc., preconditioned on the establishment of a collection system for those materials[2)].

From the above-mentioned viewpoint, JFE Steel began a waste plastics blast furnace feed project in 1996 in anticipation of enforcement of the Containers and Packaging Recycling Law. This technology is a method in which container and packaging plastics recovered by sorted collection are crushed and granulated to a size of approximately 10 mm, injected into the blast furnace together with hot blast through the tuyeres in the bottom of the furnace, and used as a reducing agent for iron ore[3)]. This technology uses the space (raceway) surrounded by coke which is formed in the furnace bottom by blowing hot blast and is a unique feature of the blast furnace. Because the granulated plastic takes the form of coarse particles, the gasification rate is slow in comparison with pulverized coal. However, since the particles are coarse, it was estimated that they were held up in

---

† Originally published in *JFE GIHO* No. 32 (Aug. 2013), p. 24–30

[*1] Senior Researcher Deputy General Manager,
Environmental Process Res. Dept.,
Steel Res. Lab.,
JFE Steel

[*3] Manager, Raw Materials Plant,
Ironmaking Dept.,
East Japan Works (Keihin),
JFE Steel

[*2] Staff Manager,
Environment & Recycling Dept.,
JFE Steel

[*4] Staff General Manager,
Coke Technology Dept.,
JFE Steel

circulation in the raceway, and as a result, gasification was possible[3]. Although coarse particles with a size of 10 mm or smaller are converted to a reducing gas by this holdup effect, issues such as pressure drop (deterioration of permeability) in the blast furnace due to the ash component originating from waste plastics became clear, and research was carried out on various improvements[4, 5]. Moreover, in responding to recent trends of high productivity operation of the blast furnace and low reducing agent rate operation for reduction of CO_2 emissions, further improvement in waste plastics gasification efficiency is necessary.

As an additional issue, because the size of the coarse plastic particles differs greatly from that of the pulverized coal used as a supplementary solid reducing agent, it is not possible to use the same equipment (storage facilities, injection equipment, etc.) in common. This means separate injection equipment must be installed and reducing agents can only be used at designated tuyeres. To increase recycling, the gasification behavior of waste plastics should desirably be as similar to that of pulverized coal as possible. It is also necessary to pulverize the waste plastics to an appropriate particle size and inject the plastic material into the blast furnace in the same manner as pulverized coal.

This paper describes knowledge in connection with the basic gasification behavior of waste plastics and the results of various tests concerning pulverization of waste plastics, and also touches briefly on a commercial waste plastics pulverization plant which was constructed based on those study results.

2. Design of Plastic Particle Size for Blast Furnace Injection

Although the gasification behavior of coal also depends on its composition, in general, coal gasification behavior depends on particle size, becoming faster as the particle size becomes smaller[6]. As with coal, the gasification behavior of plastics is also considered to be improved as the particle size decreases. However, in order to pulverize plastics, operations such as cooling, etc. are necessary, and this requires more energy. First, therefore, it is necessary to clarify the particle size at which plastics display gasification behavior similar to that of pulverized coal.

In the blast furnace, molten pig iron is produced by a process in which a hot blast with a temperature of approximately 1 200°C is blown into the furnace through tuyeres around the furnace bottom, and coke descending from the top is converted to a reducing gas, which reduces and melts the iron ore. Pulverized coal is injected through the tuyeres as a solid reducing agent in order to reduce coke consumption, and this pulverized coal is converted to a reducing gas. The solid reducing agents which are injected through the tuyeres are utilized in the blast furnace as shown in **Fig. 1**. Because the gas velocity in front of the tuyere is approximately 200 m/s, a space called a "raceway" is formed in front of the tuyere. The injected pulverized coal is converted to a reducing gas by oxygen in the blast in the raceway. Since the residence time of solids in the raceway is extremely short, being several 10 ms, unburned char (carbon; hereinafter, char) forms and is supplied to the furnace from the raceway. This char reacts with the H_2O or CO_2 that forms by reduction of iron ore and is also converted to a reducing gas, but because the descending coke reacts in the same way, char consumption is limited. In case char remains in the blast furnace, it will reduce gas permeability in the furnace and become an obstacle to passage of liquids, i.e., molten pig iron and slag droplets, causing unstable blast furnace operation. Accordingly, when selecting a supplementary reducing agent, gasification efficiency in the raceway is extremely important, and high char reactivity is desirable in case char is formed.

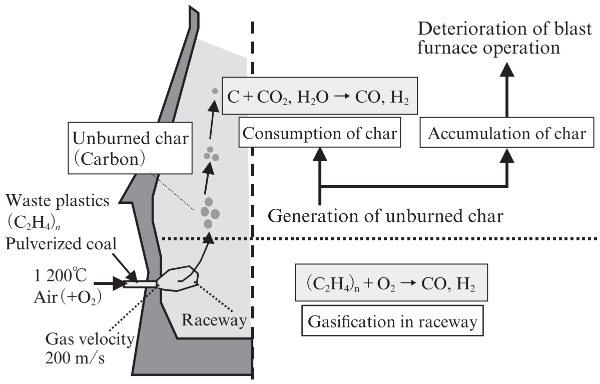


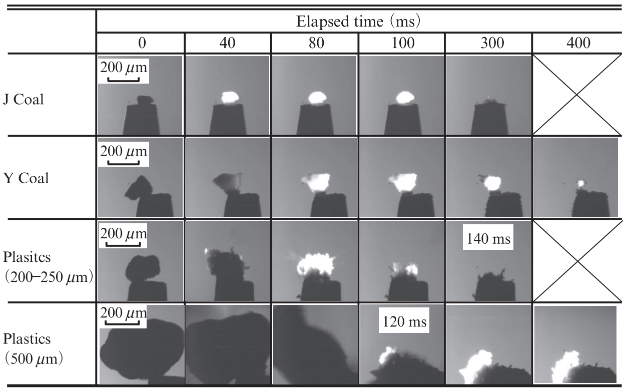
Fig. 1 Solid reducing agent behavior in blast furnace

2.1 Gasification Behavior of Single Particles

2.1.1 Experimental method

In order to evaluate the gasification behavior of single particles of plastics, plastic particles were burned by laser rapid heating and observed with a high speed CCD camera (FASTCAM-PCI, manufactured by Photron Ltd.) [7]. A single particle sampled from crushed specimen material was glued to a needle, set in the laser heater, and then irradiated with the laser (Variable output type; Maximum output of 20 W, Beam diameter: approx. 2 mm) at normal pressure in an air atmosphere, and the condition of the particle was photographed by the high speed camera (250 fps).

The sample plastic was prepared by heating and melting waste plastic (Volatile matter VM: 84.4 mass%, Fixed carbon FC: 8.2 mass%, Ash: 7.4 mass%), followed by crushing with cooling in a small-scale crusher



Atmosphere: Air Laser intensity: 3.5 W
J Coal; Volatile matter: 31.2 mass%, Fixed carbon: 58.7 mass%, Ash: 10.2 mass%
Y Coal; Volatile matter: 10.8 mass%, Fixed carbon: 77.4 mass%, Ash: 11.8 mass%

Photo 1 High speed photograph of plastics and pulverized coal

and classification by screening. Two kinds of coals were also used for comparison, J Coal (VM: 31.2 mass%, FC: 58.7 mass%, Ash: 10.2 mass%) and Y Coal (VM: 10.8 mass%, FC: 77.4 mass%, Ash: 11.8 mass%).

2.1.2 Experimental results

Photo 1 shows the condition of gasification of coals J and Y and the pulverized plastic (200–250 μm, 500 μm). J and Y Coals show the general combustion process of coal, namely, expansion of the particle due to release of the VM in the coal, combustion of the VM, formation of char, ignition of char, and combustion of char. Completion of combustion shows a tendency to be earlier when VM is higher. On the other hand, the smaller pulverized plastic particle (200–250 μm) displayed a tendency similar to coal, but the size of the particle showed a tendency to decreases as VM was released from the surface and burned. The pulverized plastic also showed good gasification behavior, as the time for completion of gasification was shorter than that of the pulverized coals. With the larger pulverized plastic particle (>500 μm), it was found that the particle volatilized while melting as it was heated, and the remaining particle adhered to the needle and underwent surface combustion.

2.2 Gasification Behavior of Particle Groups

2.2.1 Experimental method

The gasification behavior of pulverized plastics was studied using a test device simulating the bottom part of an actual blast furnace[3)]. In the tests, coke is supplied from the furnace top and hot blast is blown from the tuyeres under the same conditions as in the blast furnace. Although coke is consumed by oxygen during blowing, coke is supplied so that the charging level at the furnace top is constant. By using a probe opposite the tuyere, it is possible to measure the temperature and gas composition at arbitrary positions on the tuyere axis in the raceway. The gasification efficiency of the solid reducing agent was calculated by the following formula. The gasification efficiency shows the ratio of conversion of the solid reducing agent to reducing gas in the raceway.

(Gasification efficiency) = {(Coke supply rate when solid reducing agent is not supplied (kg/h)) − (Coke supply rate when solid reducing agent is injected (kg/h))} × (Carbon concentration in coke (mass%))/{(Injection rate of solid reducing agent (kg/h))×(Carbon concentration in solid reducing agent (mass%))}

Tests were performed under test conditions of blast temperature: 1 200°C, O_2 concentration: 24%, solid reducing agent injection rate (unit consumption): 21 kg/h (equivalent to 70 kg/t of pig iron), gas velocity in front of tuyere (actual velocity of gas injected into furnace at 1 200°C): 150 m/s, and excess oxygen ratio (blast O_2) (oxygen necessary for gasification (CO_2, H_2O) of solid reducing agent): 2.0. This test device is used mainly to evaluate gasification behavior in the raceway. For comparison, pulverized coal was used (Ash: 8.8 mass%, VM: 23.2 mass%, FC: 68.0 mass%, C: 77.1 mass%, H: 3.9 mass%, O: 8.3 mass%).

2.2.2 Experimental results

(1) Behavior of Pulverized Plastic in Furnace

Figure 2 shows the distribution of the gas composition in the raceway (the 500 mm position shows the exhaust gas composition in this test). During blowing, O_2 is used in gasification of the solid reducing agent, gradually consumed, and CO_2 and H_2O are formed as the reducing agent. The CO_2 formation peak shows the combustion focus and indicates the position where gasification is most active. The formed CO_2 and H_2O react with coke and are converted to CO and H_2. When the gasification behavior of the solid reducing agent is good, consumption of O_2 is fast. A solid reducing agent with good gasification behavior is desirable. However, if gasification is too rapid, the combustion focus will be too close to the tuyere. This is not desirable, as it places a large thermal load on the tuyere.

When the gasification behavior of pulverized plastics is compared with that of pulverized coal, gasification of pulverized plastics with sizes of 0.075 mm and 1.2 mm is extremely fast, and substantially all O_2 is consumed for gasification at a position 100 mm from the tuyere. On the other hand, with 2–4 mm pulverized plastics, O_2 remains as far as 250 mm from the tuyere, showing that gasification is slow. Pulverized plastic with a size of 1–2 mm showed a tendency similar to that of pulverized coal. The CO_2 concentra-

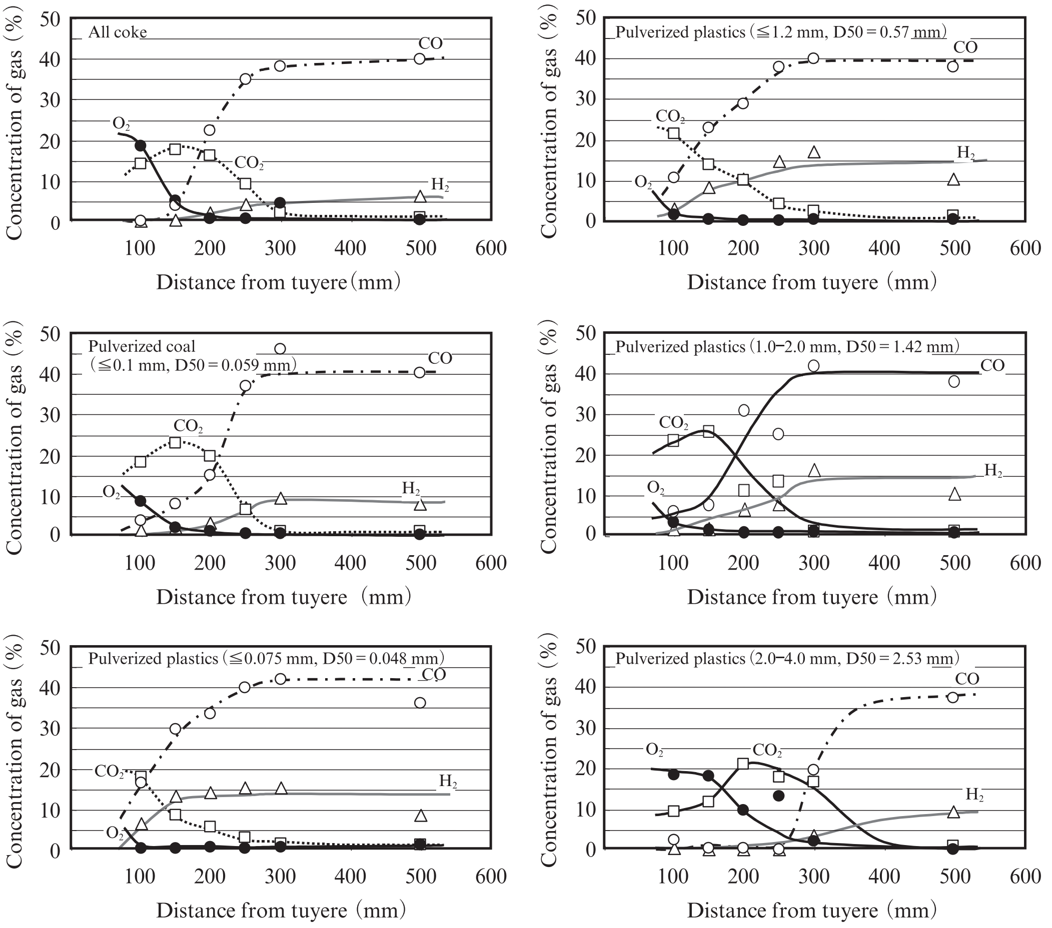


Fig. 2 Change in gas composition of raceway during solid reducing agent injection

tion, which shows the combustion focus, showed the same tendency. Thus, the O_2 consumption position shifts to the interior of the furnace as the size of the pulverized plastic increases, and the behavior of the pulverized plastic resembles that of the coke when a solid reducing agent is not injected.

(2) Gasification Efficiency of Pulverized Plastics

Figure 3 shows the relationship between the particle sizes of pulverized plastics and pulverized coal and gasification efficiency. The gasification efficiency of both solid reducing agents decreases as the particle size increases. However, in comparison with pulverized coal, pulverized plastics shows a larger decrease in gasification efficiency relative to particle size. In the case of pulverized coal, it has been reported that the VM in the particle interior is volatilized accompanying rapid heating up, and as a result, the particle size becomes smaller[8, 9]. Thus, coarse pulverized coal is atomized in the raceway, and this atomized coal then undergoes gasification. It is thought that the decrease in gasification efficiency relative to particle size was small for this reason. On the other hand, because the pulverized plastics used in these tests were materials that were produced by melt granulation of plastics with various shapes, followed by pulverization, tight particles were formed. In this case, it is considered that gasification occurs by a process in which the heat in the vicinity of the particles is transmitted to the particles, and gas volatilized from the particle surface ignites. Therefore, with pulverized plastics, the internal heat transfer in the particles is important; as the particle size increases, it is thought that heat transfer becomes rate-controlling and the

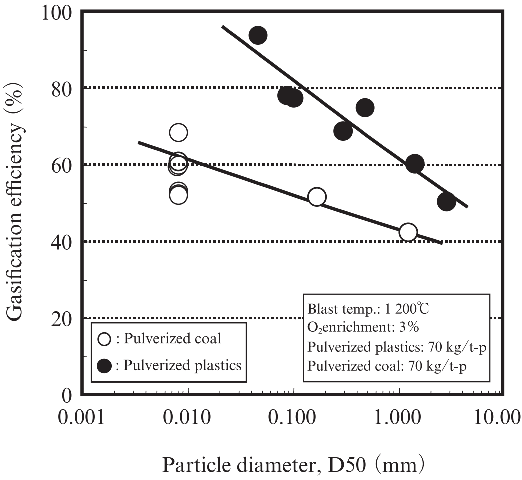


Fig. 3 Relationship between particle diameter and gasification efficiency

increment of the decrease in gasification efficiency by particle size becomes larger. Comparing gasification efficiency at the same particle size, overall, pulverized plastics show higher gasification efficiency than pulverized coal. This is because pulverized plastics consist mainly of VM, whereas pulverized coal has an FC content of 70%. It is estimated that gasification of VM is faster than gasification of FC.

In the pulverized coal that is normally used in the blast furnace, particle sizes of 75 μm and smaller comprise 80%, and in the results of these tests, gasification efficiency was in the range of 50–70%. The particle size of pulverized plastics having gasification efficiency on the same order as pulverized coal was approximately 1 mm as average particle size (D50).

2.3 Evaluation of Unburned Char of Pulverized Plastics

Pulverized plastics with a particle size of 1.2 mm and smaller showed gasification behavior similar to that of pulverized coal. However, because 100% gasification is not achieved, char forms and is supplied to the furnace. Although part of this char is consumed by gasification by CO_2, etc., the remainder accumulates in the furnace and becomes a factor causing deterioration of gas and liquid permeability. Therefore, the properties (particle size distribution, etc.) of the char formed from pulverized plastics and its CO_2 reactivity were studied.

The CO_2 gasification rate of unburned char from pulverized plastics and pulverized coal both with 1.2 mm and under was measured using a thermobalance. **Figure 4** shows the gasification rate at temperatures of 1 000°C to 1 200°C. Gasification behavior with CO_2 was evaluated by heating 25 mg of char under an inert gas and supplying CO_2 at 1.5 *l*/min after reaching the specified temperature. As shown in Fig. 4, unburned char from pulverized plastics displayed reactivity similar to that from pulverized coal.

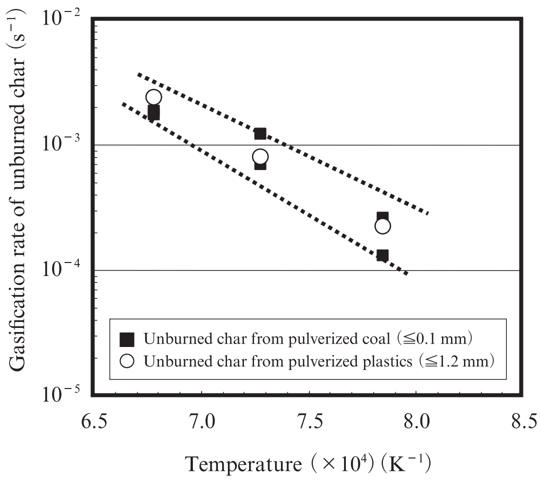


Fig. 4 CO_2 gasification of unburned char

Based on the results presented above, it is considered possible to use pulverized plastics with high gasification efficiency if the particle size is approximately 1 mm as average particle size (D50).

3. Concept of Pulverization of Waste Plastics

From the results with single particles and under conditions approximating an actual blast furnace, it was estimated that the plastic particle size which shows gasification behavior similar to that of pulverized coal is around 1 mm. Therefore, a pulverizing method which makes it possible to pulverize waste plastics to around 1 mm should be selected. However, as mentioned in Chapter 2, when pulverizing a single plastic or mixed plastics on a large scale, it is necessary to suppress softening and melting of the plastic itself accompanying pulverization. Therefore, the general practice is pulverization by cooling.

It is known that compatibilizers and elastic bodies such as rubber, etc. are mixed with plastics in order to increase the impact strength of the plastic product when mixing heterogeneous plastics[10]. Accordingly, it can be inferred that simply mixing heterogeneous plastics will cause a decrease in strength. As shown in **Fig. 5**, waste plastics are a mixture of various plastics with different properties, as well as rubber, aluminum, and other materials mixed with the plastics in the waste collection process. If these waste plastics are melted and mixed at a fine size and then cooled to room temperature, it is thought that embrittlement occurs as a result of stresses generated at the interfaces between these plastics. Moreover, as the C-C bonds in the plastics are broken by heating and melting, the plastics undergo low polymerization, and in the case of polyvinyl chloride (PVC), a dechlorination reaction occurs at temperatures over 200°C[11], forming carbonaceous chlorides[12]. Accordingly, it is considered possible to pulverize plastics at

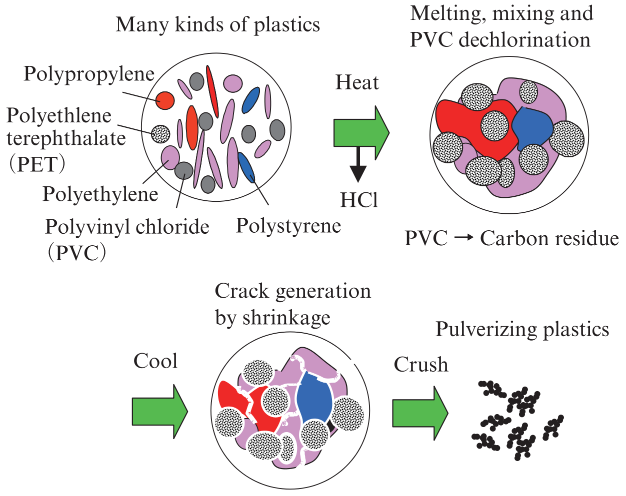


Fig. 5 Concept of waste plastics pulverizing

room temperature, even with conventional pulverizing equipment, by heating, melting, and mixing the waste plastics.

4. Verification of Pulverization of Waste Plastics

4.1 Experimental Method

Because the waste plastics used in tests were waste plastics collected under the Containers and Packaging Recycling Law, unsuitable impurities (glass, metal, etc.) were removed, after which melt granulation to a cylindrical shape (10 mmφ) was performed with a ring die granulation machine. The apparent density of the granulated plastic was 0.83 g/cm^3. The results of elemental analysis were C: 75.8 mass%, H: 10.25 mass%, O: 8.80 mass%, Cl: 1.46 mass%, ash: 3.47 mass%. From measurement by proton nuclear magnetic resonance (^{1}H-NMR), the plastic composition of the waste plastics was polyethylene: 31.4%, polypropylene: 22.4%, polystyrene: 16.9%, polyethylene terephthalate (PET): 12.9%, PVC: 1.6%, and other plastics: 13.8%.

The tests were performed with the twin-screw extruder (Labo Plastomill, Manufactured by Toyo Seiki Seisaku-sho, Ltd.; Screw diameter: 20 mmφ, Die diameter: 10 mmφ, Screw length/Screw diameter ratio: 20) with a four-section electric heater (also including die heating part) shown in **Fig. 6**. The test conditions were treatment temperature: 180–350°C and waste plastics supply rate: 0.50 kg/h (residence time: 15 min), 0.25 kg/h (30 min), and 0.17 kg/h (45 min). Molten plastic discharged from the die was cooled and recovered.

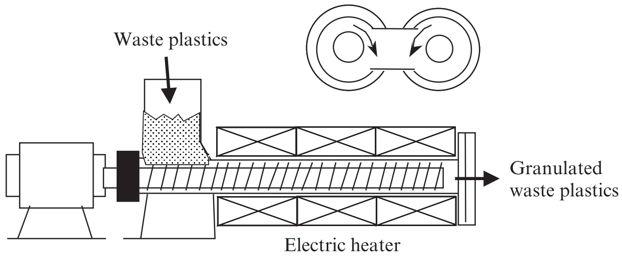


Fig. 6 Experimental apparatus for waste plastics granulation

Approximately 200–300 g (cut to approx. 3 cm) of the waste plastics obtained by heating and melting was sampled and crushed for 15 min (695 rpm) by using a crusher (UM-280, Manufactured by Horai Co., Ltd.) equipped with a 2 mmφ screen (punching metal). The obtained under 2 mm specimen was classified by screening, weight measurements were performed by particle size, and the average particle size was obtained from a Rosin-Rammler diagram.

4.2 Results and Discussion

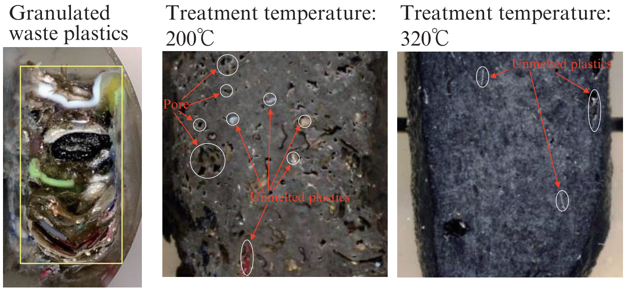


Photo 2 Cross section of granulated waste plastics

Photo 2 shows the external appearance and cross-sectional photographs of the waste plastics obtained by heating and melting (residence time: 30 min). The waste plastics obtained with the treatment temperature of 200°C contained numerous internal pores and scattered unmelted plastic, indicating that mixing was inadequate. On the other hand, at 320°C, porosity decreased and satisfactory mixing was observed. The presence of rubber, aluminum, and other foreign matter in the waste plastics could also be confirmed. When the viscosity of the waste plastics was measured (Flow Tester CFT-500, Manufactured by Shimadzu Corp.), the results were 3 000–5 000 Pa·s with the 200°C material and 400–550 Pa·s with the 200°C material. This reduction in viscosity is attributed to melting of the unmelted plastic at 320°C. Melt mixing improved as the treatment temperature increased. Measurements of bulk density (tight) after crushing the obtained melted plastic to under 2 mm showed results of 0.45 g/cm^3 with treatment at 200°C and 0.48 g/cm^3 with treatment at 320°C.

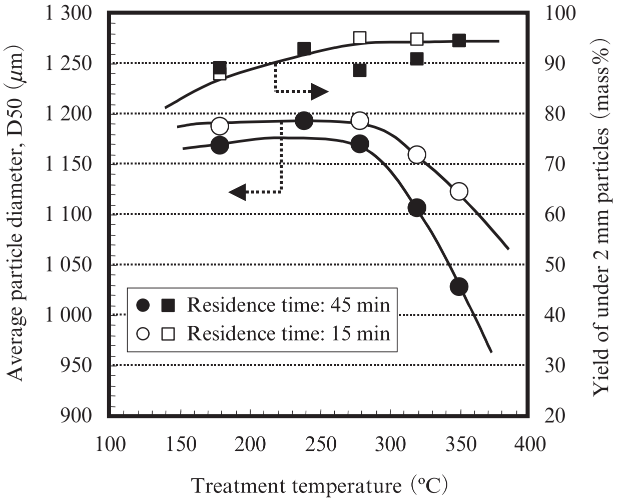


Fig. 7 Influence of treatment temperature on average particle diameter and yield of >2 mm of waste plastics

After heating and melting, crushing was performed with a small-scale crusher. Because the crusher is equipped with a 2 mm screen, all the plastic will be reduced to a particle size of under 2 mm if crushability is extremely high, but in case of poor crushability, some will remain in the crusher. **Figure 7** shows the relationship between the treatment temperature, yield of under

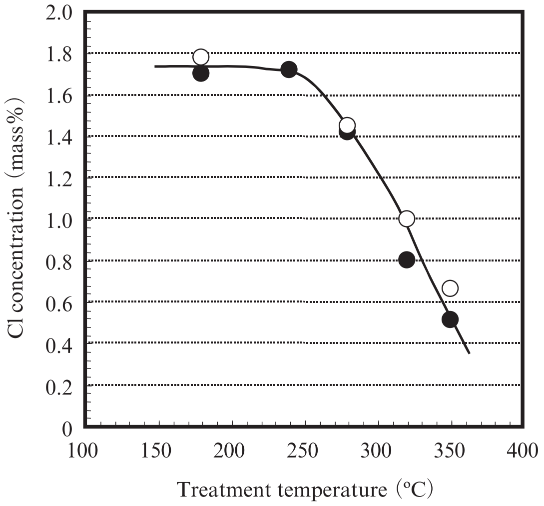


Fig. 8 Relationship between Cl concentration and average particle diameter of crushed waste plastics

2 mm plastic particles, and average particle size (D50: 50% Passage diameter). Yield of under 2 mm plastic particles increased as the treatment temperature increased. Virtually no effect of residence time was observed. On the other hand, no effect of the treatment temperature on the average particle size of the under 2 mm plastic can be observed up to 280°C, but above this temperature, the average particle size decreases greatly.

Figure 8 shows the relationship between the treatment temperature and the Cl concentration in the obtained waste plastics. At treatment temperatures of 250°C and higher, the Cl concentration decreased due to the dechlorination reaction of PVC. If this result is considered together with the results in Fig. 7, the main factor in improved crushability is considered to be the existence of dechlorinated matter formed by the dechlorination reaction of the PVC in the waste plastics. This dechlorinated matter is thought to be carbonaceous (under the treatment temperature condition) with a polyene structure, and this is easily crushed by impact[12, 13]. It is thought that the dechlorinated matter is uniformly distributed in the waste plastics by melt mixing, and this serves as points of origin for destruction of the plastic.

The factors which increase the yield of under 2 mm particles accompanying heating are considered to be as follows:

(1) Breakage of the main chain of the plastic accompanying heating, resulting in low polymerization[14].
(2) Increase in the contact interface between different plastics by melt mixing of heterogeneous plastics and generation of stresses at those interfaces in the cooling process, which then become points of origin for destruction of the plastic.
(3) Because rubber, aluminum, paper, wood, etc. are mixed in waste plastics, these are dispersed by the waste plastics melt mixing process; stresses are generated at the interfaces between those impurities and the plastics in the cooling process, and these positions become points of origin for destruction of the plastic.

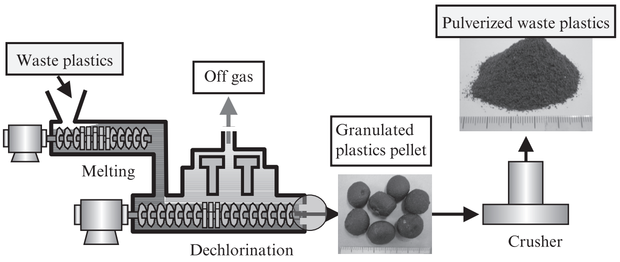


Fig. 9 Schematic diagram for pulverization of waste plastics

5. Waste Plastics Pulverization Process

Based on the results of the gasification tests and waste plastics pulverization tests, the waste plastic pulverization process shown in **Fig. 9** was constructed in March 2007 at East Japan Works (Keihin), JFE Steel. This process comprises a melting and kneading process, in which waste plastics consisting of different types of plastics are melted and uniformly mixed, a dechlorination process which removes chlorine from PVC in the waste plastics as hydrogen chloride, a water cooling process for forming cracks (stress) in the uniformly kneaded plastics, and a process for pulverizing the plastic by an impact-type crusher. This plant produces 8 000 t per year of pulverized plastics (Average particle size: 0.2–0.4 mm). Further improvements have been added, and the equipment composition now enables pulverization by only heating and melting. Following an expansion of the facility during fiscal year 2012, the plant now has a capacity of 16 000 t per year. The plant is reducing CO_2 emissions by reducing use of coke, which is a natural resource.

6. Conclusions

A gasification study of plastics with different particle sizes and a study of a heating, melting, mixing, and crushing method for waste plastics were carried out. The following results were clarified.

(1) Based on the gasification behavior of single particles and particle groups, if the size of crushed plastics is 1.4 mm or less, it was estimated that the plastic would show gasification behavior similar to that of pulverized coal.
(2) In order to improve the crushability of waste plastics, heating, melting, and mixing waste plastics at a temperature above the dechlorination temperature of polyvinyl chloride is effective.

(3) Based on these study results, the waste plastics pulverization process was applied to a practical operation, and the pulverized plastics are now being utilized as a supplementary solid reducing agent for iron ore at a blast furnace.

References

1) http://www.pwmi.or.jp/flow/flame04.htm.
2) http://www.jisf.or.jp/business/ondanka/index.html.
3) Asanuma, Minoru; Ariyama, Tatsuro; Sato, Michitaka; Murai, Ryota; Nonaka, Toshiharu; Okochi, Iwao; Tsukiji, Hideaki; Nemoto, Kenichi. Development of Waste Plastics Injection Process in Blast Furnace. ISIJ Int. 2000, vol. 40, p. 244.
4) Murai, Ryota; Asanuma, Minoru; Kashihara, Yuichi; Sato, Michitaka; Ariyama, Tatsuro; Fukumoto, Yasuhiro; Sakurai, Masaaki. CAMP-ISIJ. 2005, vol. 18, p. 97.
5) Asanuma, Minoru; Kajioka, Masahiko; Kuwabara, Minoru; Fukumoto, Yasuhiro; Terada, Kaneo. Establoshment of Advanced Recycling Technology for Waste Plastics in Blast Furnace. JFE Technical Report. 2009, no. 13, p. 34.
6) Hirano, Toshisuke. Nenshougaku—Nenshougenshou to sono Seigyo—. Kaibundou Shuppan, 1986, p. 162.
7) Taniguchi, Masayuki; Chen, John C.; Narato, Kiyoshi; Ito, Kazuyuki; Miyadera, Hiroshi; Kudo, Kazuhik. Fossil Energy. Ignition and Combustion Properties of Pulverized Coal Suspended in Laminar Upward Flow Under High Heating Rate Condition. Kagakukougakuronbunshu. 1994, vol. 20, p. 834.
8) Willmers, R. Ironmaking Conference Proceeding. 1989, p. 395.
9) Yamaguchi, Kazuyoshi; Uno, Takeo; Deno, Tadashi; Yamane, Kenji; Tono, Ikuo; Hirakawa, Shunichi. Combustion and Reaction of Coarse-sized Pulverized Coal in Blast Furnace. Tetsu-to-Hagané. 1998, vol. 84, p. 603.
10) Narisawa, Ikuo. Purasuchiku no Taishougekisei. Shiguma Shuppan, 1994.
11) Plastc data handbook. Asahikasei Amidas. Kougyo-Chousakai, 1999.
12) Asanuma, Minoru; Ariyama, Tatsuro; Iemoto, Mikoto. Development of Dechlorination Process for PVC in Waste Plastics. J. Jpn. Inst. Energy. 2000, vol. 79, p. 210.
13) Shin, S. M.; Yoshioka, Toshiaki; Okuwaki, Akitsugu. Fundamental Degradation Behavior of PVC Materials in Aqueous Solutions at Elevated Temperatures. Proc. 1st Inter. Symp. on Feedstock Recycling. Sendai, 1999, SV-9, p. 87.
14) Hirano, Katsumi; Iwasaki, Nobuhisa; Kakuta, Yusuke; Sugano, Motoyuki. Study on the Retention of Strength in Material from Recycled PET Bottles. J the Japan Society of Material Cycles and Waste Management. 2010, vol. 21, p. 165.