# Establishment of Advanced Recycling Technology for Waste Plastics in Blast Furnace<sup>†</sup>

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#### Abstract:

The establishment of technology for recycling waste plastics is a highly important issue for global environmental conservation and the society. JFE Steel has pursued the effective use of waste plastics as a reducing agent for injection into blast furnaces, and conducted hot model experiments to study the combustion and gasification behaviour of waste plastics. On the basis of this basic investigation, advanced technologies that can further improve the combustion and gasification efficiency of waste plastics even with low strength has been developed; i.e. in order to improve combustibility of fine waste plastics, technology for simultaneous injection of such plastics with pulverized coal and/or natural gas has been developed. For improved the strength of plastics, technology for combined agglomeration of waste plastics with CaCO<sub>3</sub> has been developed. In addition, technology for fine crushing of waste plastics has been studied on the basis of new ideas, and this technology has been applied in actual plant operation. These technologies have been successfully applied in actual blast furnaces, contributing to lowering the reducing agent rate.

## 1. Introduction

Since the 1990s, global warming caused by  $CO_2$  and other factors has become remarkable at the global scale.

<sup>†</sup> Originally published in *JFE GIHO* No. 22 (Nov. 2008), p. 67–72



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\*2 Senior Researcher Deputy General Manager, Ironmaking Res. Dept., Steel Res. Lab., JFE Steel The IPCC recently issued a report containing detailed predictions of the future, which included a global rise in temperatures due to greenhouse gases (GHG) and the effects of those higher temperatures<sup>1</sup>). To prevent these problems, the Kyoto Protocol, which aims at reducing  $CO_2$  emissions at the global scale, took effect in 2005, requiring an average reduction of at least 5% from the level in 1990 over the 5 year period from 2008 to 2012 by the advanced nations which ratified the Protocol. Under the Kyoto Protocol, Japan is committed to a 6% CO<sub>2</sub> reduction target. However, because the dramatic economic growth of the BRICs nations, beginning with China, in recent years has caused further increases in CO<sub>2</sub> emissions, a more drastic reduction in CO<sub>2</sub> emissions has become necessary. Reduction targets for post-2013 were discussed in the G8 (Lake Toya Summit) in July 2008, resulting in a common target of reducing  $CO_2$  emissions by one-half by 2050.

On the other hand, because Japan is extremely dependent on foreign sources of natural resources, recycling and effective utilization of wastes is an urgent issue in this country. Therefore, the Basic Law for Establishing the Recycling-Based Society was enforced in 2001 with the aim of promoting recycling of various types of wastes in order to create a material circulationtype recycling society. In order to promote treatment of waste plastics as one type of waste, the Law for Promotion of Sorted Collection and Recycling of Containers



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and Packaging (commonly known as the Container and Packaging Recycling Law) was fully enforced in 2000, covering containers and packaging in municipal solid waste. The effects of enforcement of this law have become apparent, as can be seen in the increase in the effective utilization rate of waste plastics from 46% in 1999 to 72% by  $2006^{2}$ ).

Japanese industry also takes the problem of global warming seriously, and respective industries have worked out policies or Voluntary Action Plans for reducing CO<sub>2</sub> emissions and decreasing energy consumption. As a Voluntary Action Plan for measures to prevent global warming, Japan Iron and Steel Federation, which is an energy intensive industry, has set a target of reducing average energy consumption during the period 2008–2012 by 10% from the 1990 baseline, assuming annual crude steel production of 100 million tons. As a supplementary target, the steel industry has also incorporated use of 1 million tons per year of waste plastics, preconditioned on the establishment of a waste plastics collection system. Accordingly, it can be said that the establishment of recycling technologies for waste plastics is an extremely important issue not only for Japanese society, but also for the preservation of the global environment.

Anticipating enforcement of the Container and Packaging Recycling Law, JFE Steel began use of industrial waste plastics as blast furnace feed in 1996, and began a waste plastics blast furnace recycling business responding to the above-mentioned Recycling Law in 2000<sup>3,4)</sup>. Eight years have already passed since the start of this blast furnace waste plastics recycling business under the Law. During this period, JFE Steel has achieved cumulative recycling of approximately 480 000 tons of waste plastics (2000–2007). Although various problems arose at the start of operation, process improvements have been implemented. At present, the waste plastics used in blast furnaces consist of crushed plastics and granulated plastics, in both cases with a size of 10 mm or less. Using the function of the blast furnace raceway, these are converted into a reducing gas by the hold-up effect of the raceway. However, practical operation revealed various problems, including an increase in pressure drop in the blast furnace (deterioration of furnace permeability) due to the ash component originating from waste plastics. Moreover, in recent high productivity operation with a low reducing agents rate, which has been adopted from the viewpoint of reducing CO<sub>2</sub> emissions, further improvement in the combustion and gasification efficiency of waste plastics is necessary. In the future, it appears that advanced technical development to further improve the combustibility of waste plastics will be necessary in order to maintain stable blast furnace operation while continuing to increase the waste plastics injection rate. From this viewpoint, JFE Steel is actively promoting the development of a technique for simultaneous injection of waste plastics with pulverized coal or natural gas, a combined agglomeration technique using a solid aggregate<sup>5)</sup>, and a production technology for pulverized waste plastics<sup>5)</sup>.

This paper describes, firstly, basic knowledge in connection with the combustion and gasification behavior of waste plastics. This is followed by an introduction of various technical developments carried out to improve that behavior, and finally, a discussion of results in which drastic improvement was achieved in the combustibility of waste plastics.

# 2. Improvement of Combustibility of Existing Waste Plastics

# 2.1 Study of Mixed Injection with Pulverized Coal and Natural Gas

The appearance of the two types of waste plastic particles which are currently injected into the blast furnace is shown in Photo 1. One type is produced by crushing solid plastics, and the other, by granulating film-shaped plastics. In comparison with pulverized coal, these plastics have a dense structure and low specific surface area per unit of weight. Because the mode of combustion behavior of waste plastics in a high temperature field is estimated to be surface combustion<sup>3)</sup>, in order to enhance the combustibility of the waste plastics, it is desirable to add a material with a higher combustion velocity as an accelerator. Use of the acceleration effect of pulverized coal or natural gas, which have higher combustion velocities than waste plastics, is considered to be an effective means of realizing this effect. Figure 1 shows the temperature distribution in the raceway when pulverized coal, methane (simulating natural gas), and waste plastics were injected individually into a coke packed bed (apparatus used in hot model experiments)<sup>3)</sup> simulating the bottom of the blast furnace. The figure shows that the combustion velocity increases as the maximum temperature position approaches the injection point



Photo 1 Appearance of waste plastics



Fig. 1 Temperature change in raceway on injection of PC, CH₄ and waste plastics

(tuyere nose). As shown in the same figure, methane has the highest combustion velocity, followed by pulverized coal and waste plastics in that order.

Therefore, first, the effect of mixing with pulverized coal was studied. Using the above-mentioned hot model experiment apparatus, tests were conducted with different methods of mixing waste plastics and pulverized coal. The results are shown in **Fig. 2**. Case 1 is the case of separate injection of waste plastics and pulverized coal using lances. Case 2 is the result of injection after mixing in the piping. In comparison with Case 1, an improvement of approximately 10% in the combustion and gasification efficiency was confirmed with Case 2.



Fig.2 Effect of simultaneous injection on combustion and gasification efficiency of solid injectants

This is estimated to be the result of acceleration of the combustion and gasification velocity of the waste plastics by the pulverized coal, which has a higher combustion velocity. Figure 3 shows the change in the velocities of plastic and pulverized coal particles injected in a 120 m/s gas stream. Although both types of particles are accelerated by the gas stream, the increase in the velocity of the plastic particles is delayed in comparison with the pulverized coal because the plastic particles are larger. This suggests residence time in the raceway in the furnace bottom. Because the residence time of the waste plastics is longer than that of the pulverized coal, this point shows that mixing with pulverized coal is advantageous for combustion. On the other hand, adhesion of pulverized coal to the surface of the waste plastics particles after mixing in the piping was confirmed, as illustrated in Fig. 3. This suggests that the combustion heat of the pulverized coal is supplied directly to the plastics, and thus accelerates combustion and gasification of the plastics. Because this adhesion also increases



Fig. 3 Mechanism of increase in combustion and gasification efficiency

		А	В	С	D	Е	F	G	Н	Ι
PCR	(kg/t)	100	100	130	130	70	100	130	160	190
WPR	(kg/t)	30	30	30	30	30	—	—	—	—
CH <sub>4</sub> . R	(kg/t)		30	—	30	30	30	—	30	_
O <sub>2</sub> enr.	(%)	1.0	4.0	2.0	6.0	3.0	3.0	3.0	6.0	3.0
Blast Temperature	(°C)	1 200								
V <sub>tuy</sub>	(m/s)	150								
Ex. O <sub>2</sub>		0.91	0.75	0.77	0.70	0.87	0.88	0.94	0.70	0.66

Table 1 Experimental conditions of raceway hot model

Theoretical flame temperature (TFT): Constant

PCR: Pulverized coal rate WPR: Waste plastics rate CH<sub>4</sub>. R: Methane rate O<sub>2</sub> enr.: Enrichment Ex. O<sub>2</sub>: Excess O<sub>2</sub> ratio

the residence time of the pulverized coal in the high temperature field, it is also considered to improve the combustibility of the pulverized coal.

Next, the effect of simultaneous injection of pulverized coal and natural gas with waste plastics was examined. As the waste plastics, agglomerated plastics were used (however, the harmonic mean size was approximately 4 mm). Two lances were inserted in the blowpipe, and a mixture of agglomerated plastics and pulverized coal was injected from one side, while methane gas was injected from the other to simulate natural gas. The agglomerated plastics and pulverized coal were mixed in the piping at the upstream side of the lance. The experimental conditions are shown in **Table 1**. Under all injection conditions, the blast temperature and the tuyere gas velocity were held constant. The oxygen enrichment rate was also adjusted so that the adiabatic theoretical flame temperature would be constant.

Figure 4 shows the relationship between the excess oxygen ratio (ratio of the oxygen concentration in the



Blast temperature: 1 200°C Waste plastics: 30 kg/t Methane rate: 30 kg/t Pulverized coal rate: 70–190 kg/t Theoretical flame temperature: Constant

Fig.4 Effect of methane gas injection on combustion efficiency of solid injectants

blast to the oxygen concentration necessary for perfect combustion of the injectants) and the combustion and gasification efficiency. The total combustion and gasification efficiency of the solid reducing agents (pulverized coal, waste plastics) was increased by simultaneous injection of methane. This is assumed to be because methane has an extremely fast combustion velocity, as mentioned previously, and forms a high temperature field which accelerates combustion and gasification of the pulverized coal and waste plastics.

This result is attributed to an effect in which combustion of both pulverized coal and waste plastics is accelerated by the mechanism described above. In other words, because the pulverized coal adheres to the surface of the waste plastics, it can be expected that the combustion heat of the pulverized coal will be transmitted effectively to the waste plastics by the simultaneous flight motion of the two materials. Because natural gas forms a high temperature field by rapid combustion, it increases the combustion velocity of the waste plastic itself.

Based on this result, operation with simultaneous injection of pulverized coal and natural gas with waste plastics is now used.

### 2.2 Improvement of Agglomerated Plastics by Addition of CaCO<sub>3</sub>

The current waste plastics blast furnace recycling technology uses either crushed plastics or agglomerated plastics with sizes of 10 mm or less. Although coarse plastics are inferior in combustibility, the combustion and gasification efficiency is improved by circulating combustion in the blast furnace raceway. When considering circulating combustion, the strength of the agglomerated plastics is important. Because low strength agglomerated plastics are easily powdered (reduced to fine particles) in the transportation and combustion processes, the factors which reduce the combustion and gasification efficiency were obtained as fundamental experimental knowledge<sup>3</sup>). Furthermore,

because slag-forming of the ash component in waste plastics is difficult due to the high melting point of the ash (approximately 1 750°C), the ash component causes increased pressure drop in the blast furnace. Therefore, in order to expand the use of waste plastics in the future, it will be necessary both to improve the combustion and gasification efficiency and to promote slag-forming of the ash in the waste plastics in order to improve furnace permeability by producing agglomerated plastics which are resistant to powdering (improvement of strength of agglomerated plastics). As a means of achieving this, combined agglomeration, in which the waste plastics are agglomerated together with an aggregate during waste plastic agglomeration, is considered effective. As the aggregate, the authors focused on CaCO<sub>3</sub>. This was because  $CaCO_3$  is assimilated with the raceway shell and thus has the combined effect of lowering the melting point of the shell<sup>5</sup>).

Photo 2 shows a cross-sectional photograph of combined agglomeration particles produced with an extrusion granulator when 3 wt% of CaCO<sub>3</sub> was added to the waste plastics, together with the result of measurement of the distribution of Ca atoms by EPMA. From this figure, it can be understood that the voids in the agglomerate are adequately filled with CaCO<sub>3</sub>. Furthermore, with samples containing 3-5 wt% of CaCO<sub>3</sub>, it was confirmed that the compressive strength index  $\sigma$  (index showing the hardness of the particles after agglomeration) increased by more than two times, from 98 to 245 N/mm.

A hot model experiment was carried out using combined agglomerated plastics having CaCO<sub>3</sub> contents from 3-5 wt%. The results are shown in Fig. 5. This figure illustrates the relationship between the harmonic mean diameter, the mean strength index  $\sigma$ , and the combustion and gasification efficiency  $\eta$ . As a general trend, this figure clearly shows that, in the region where both the harmonic mean diameter and the mean strength index are high, the combustion and gasification efficiency  $\eta$  is also high. Similarly, with the combined agglomerated



Granulated plastics

Appearance of combined agglomeration of waste Photo 2 plastics with CaCO<sub>3</sub>

plastics in this experiment, it can be understood that  $\eta$ also increases as a result of increasing strength. Accordingly, it is considered that a combustion and gasification efficiency of more than 90% can be secured by using a mean diameter of approximately 4.5 mm or more and waste plastics having  $\sigma \ge 118$  N/mm, as shown by the hatched region in the figure.

Figure 6 shows the relationship between the elapsed injection time of CaCO3-added agglomerated plastics and pulverized coal and blast pressure in the hot model experiment. Although the apparatus used in this experiment simulates the bottom of the blast furnace, the increase in pressure drop is remarkably apparent because there is no dropping of molten iron and slag. With the conventional agglomerated plastics shown in the same figure, the blast pressure increases with elapsed time. On the other hand, with the CaCO<sub>3</sub>-added agglomerated plastics (3-12% CaCO<sub>3</sub>), no increase in



Fig. 5 Relationship among harmonic mean diameter, mean strength index and combustibility



Blast temperature: 1 200°C O<sub>2</sub> enrichment: 3% Plastics rate: 70 kg/t-p Pulverized coal rate: 70 kg/t-p

Fig.6 Change in blast pressure of raceway hot model experiment

blast pressure was observed. Samples of the shell were taken after the tests were completed, and X-ray diffraction measurements were performed. As a result, with the conventional agglomerated plastics, the shell consisted of Mullite  $(3Al_2O_3 \cdot 2SiO_2)$ , but with CaCO<sub>3</sub> addition, the shell consisted of Anorthite (CaO·Al<sub>2</sub>O<sub>3</sub>·2SiO<sub>2</sub>), which is a low melting point slag. Thus, assimilation of Ca was observed. Based on the results described above, it can be inferred that the CaCO<sub>3</sub> which was added to the plastic promoted slag forming/reduction of the melting point, and thereby alleviated pressure drop in the furnace.

This technology has been adopted at No. 3 blast furnace at JFE Steel's West Japan Works (Fukuyama District) and is making an important contribution to reduction of the coke ratio and improvement of furnace bottom permeability.

# 3. Development of Waste Plastics Pulverization Technology

Recent blast furnace operation has been characterized by high production (high productivity), low reducing agents ratio operation, and as a result, use of auxiliary reducing agents blown from the tuyeres has become more important that in the past. As auxiliary reducing agents, materials with a higher combustion velocity are desirable. Because agglomerated plastics are coarse particles, and therefore have a small specific surface area, their combustion velocity is small in comparison with pulverized coal. It can be said that the raceway function compensates for this difference. However, to increase the combustion velocity of waste plastics, it is necessary to pulverize the material. Pulverized waste plastics undergo one-pass combustion in the raceway, and circulating combustion like that with coarser plastics cannot be expected. This means that the combustion and gasification efficiency depends on the combustion velocity. Accordingly, a technology for pulverizing the waste plastics to the proper diameter is necessary. Based on these considerations, the authors undertook the development of a pulverization technique for waste plastics, which had been difficult by conventional methods, and investigated application to waste plastics recycling in the blast furnace.

### 3.1 Concept of Pulverization of Waste Plastics and Combustibility of Product

When pulverizing a single plastic or mixed plastics, pulverization was normally difficult because the heat of the plastic itself increased due to the energy associated with pulverization, causing the plastic to soften and melt. Therefore, the general practice was conventional crushing by cooling. However, in basic experiments, it was found that, if plastics with different properties are melted and mixed in a fine mixture and then cooled to room temperature, stresses are generated at the interfaces between the heterogeneous plastics, resulting in embrittlement, as illustrated in **Fig. 7**. Accordingly, it is considered possible to perform pulverization at room temperature using the type of pulverizer employed in the past.

Finer pulverization is advantageous from the viewpoint of combustibility, but there is a proper particle diameter from the viewpoint of handling. Assuming the particle size after crushing, the same combustibility (combustion rate, combustion velocity) as with pulverized coal was adopted as an index. **Figure 8** shows the relationship between the harmonic mean diameter and combustion and gasification efficiency. With the same particle diameter, approximately 10% higher combustion and gasification efficiency was obtained in comparison



Fig. 7 Concept of waste plastics pulverizing



Fig. 8 Effect of particle diameter on combustion and gasification efficiency of plastics



Fig. 9 Advanced plastics recycling process (APR)

with pulverized coal. Accordingly, the harmonic mean diameter of plastics for obtaining the same combustibility as the pulverized coal which is normally used can be estimated at approximately 0.2–0.4 mm from Fig. 8.

#### 3.2 Advanced Plastics Recycling Process

Based on the results of the fundamental study of combustibility and other behavior, a waste plastics pulverization process (Advanced Plastics Recycling Process: APR) with the flow shown in **Fig. 9** was constructed at JFE Steel's East Japan Works (Keihin District) in March 2007. These facilities comprise a melting/mixing process, dechlorination process, and crushing process for waste plastics, and produce 8 000 t/y of pulverized plastics (mean diameter 0.2–0.4 mm). At present, this plant is operating smoothly and is contributing to reduction of the blast furnace reducing agent consumption.

#### 4. Conclusions

In order to improve the combustion and gasification efficiency of small particle/low strength agglomerated plastics, the following technical developments were carried out, and an advanced recycling technology which is applicable to all types of plastics was completed.

- Increase of strength of waste plastics by combined agglomeration with CaCO<sub>3</sub>.
- (2) Improvement of combustibility of waste plastics by simultaneous injection with pulverized coal and natural gas.
- (3) Development of Advanced Plastics Recycling Process (APR Process) for pulverized waste plastics.

If waste plastics are considered to be carbon neutral materials, this technology has a large effect in reducing generation of  $CO_2$ . In the future, the authors will endeavor to expand the use of waste plastics.

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