Material Modification Technologies for Plastics in Closed-Loop Recycling System

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1. Introduction

Mitsubishi Electric Corporation has been promoting 3R (reduce, reuse, and recycle) with the aim of realizing sustainable resource circulation for a recycling-oriented society. For example, to recycle plastics contained in discarded household appliances, Mitsubishi Electric introduced lines with an annual throughput of approximately 15,000 tons at Green Cycle Systems Corporation, an affiliated company, in April 2010 to automatically sort polypropylene (PP), polystyrene (PS), and acrylonitrile–butadiene–styrene (ABS) copolymers. Mitsubishi Electric has realized "closed-loop recycling from household appliances to household appliances" in which PP, PS, and ABS are collected from plastics contained in discarded household appliances and sorted for recycling. They are then applied to household appliances such as air conditioners and refrigerators.[1] Figure 1 shows the closed-loop recycling flow that Mitsubishi Electric has established. To increase the number and types of parts to which closed-loop recycling is applied, material modification technologies are required for exterior parts and functional parts.

Recycling into only deep-colored (black and gray) interior parts used to be possible in closed-loop recycling.[2][3] This paper describes the material modification technologies for plastics required to expand the scope of closed-loop recycling, in other words, to allow the recycling of applied parts into exterior parts and functional parts.

2. Expansion of Closed-Loop Recycling

This paper describes several material modification technologies for plastics toward the expansion of closed-loop recycling: Technology for lightening the color of recycled PP using color sorting equipment, technology for making recycled PS flame-resistant using the cabinets at the back of discarded TVs (discarded TV back cabinets), technology for removing contamination from the surface of recycled PP by polishing the surface of plastic flakes, and technology for improving the impact strength of recycled PP using low-cost tubes.

3. Material Modification Technologies for Plastics

3.1 Technology for lightening the color of recycled PP

Refrigerators, air conditioners, and washing machines are called white goods and they include many white parts. To increase the number and types of parts to which closed-loop recycling is applied, recycling into white (light color) parts is necessary. However, recycled flakes as shown in Fig. 1 are a mixture of white, black, gray, and other colors. When they are melted and

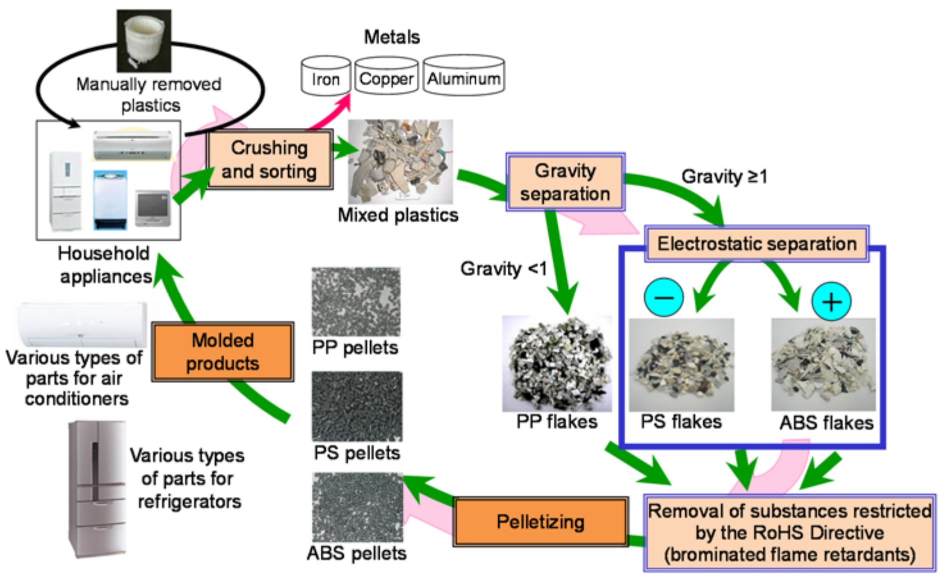

Fig. 1 Flow chart of closed-loop plastic recycling technologies

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blended to make raw materials (turned into pellets), the color of the obtained pellets is gray (Munsell color value 5.2 for recycled PP). The Munsell color value shows the degree of brightness of a color based on the decimal system. Black (minimum brightness) is zero and white (maximum brightness) is ten on the scale.

One method for lightening the color of plastics is the addition of titanium dioxide, which works as a white colorant. However, adding titanium dioxide decreases the impact strength. Therefore, we decided to use color sorting equipment to separate the deep-colored flakes and lighten the color of the recycled PP. Separating the flakes with a Munsell color value equal to or smaller than the designated value (e.g., 7.6) from the recycled PP flakes makes it possible to obtain light-colored pellets with a Munsell color value of 7.9. In addition, adding a small amount of titanium dioxide can adjust the Munsell color value equal to or more than 8.0, which makes it possible to use recycled PP for light-colored parts.

Example parts that were closed-loop recycled by lightening the color of recycled PP are the partition walls between refrigerator cells, as shown in Fig. 2.

Fig. 2 Example of the parts of a refrigerator using light-colored recycled PP

3.2 Technology for making recycled PS flame-resistant

A large quantity of different types of flame-resistant parts are used around the substrate in household appliances, so making recycled plastics flame-resistant will likely increase the quantity of recycled plastics to be used. However, flame retardants are more expensive than resin. As higher flame retardancy is required, the amount to be added must be increased, which tends to increase the material cost. Therefore, in place of a flame retardant, Mitsubishi Electric decided to use the back cabinets of discarded TVs (only those with brominated flame retardants that are not prohibited by the RoHS Directive) collected by Hyper Cycle Systems Corporation (household appliance recycling plant). Table 1 lists the flammability properties of recycled PS and discarded TV back cabinets.

Although the flammability of the back cabinets varies from V-2 to V-0, it is equal to or higher than V-2, so adding them can reduce the amount of flame

Table 1 Flame-retardant characteristics of exterior parts of discarded televisions

Raw material / Physical property	Recycled PS	Discarded TV back cabinet
Flammability (UL94 standard)	Horizontal burning/1.5 mm Without self-extinguishing properties	V-2 to V-0/1.5 mm With self-extinguishing properties

retardant to be added. The flammability of parts around the substrate of an air conditioner needs to be V-0 at 1.5 mm. Therefore, for the developed flame-resistant recycled PS, recycled PS and discarded TV back cabinets were mixed in equal proportions so as to satisfy this requirement and then flame retardant was added. The amount of flame retardant added to the developed material could be reduced to half compared to a material that was made flame-resistant using only recycled PS without adding the discarded TV back cabinets, so the cost of flame-resistant recycled PS can be reduced.

Example parts that were closed-loop recycled by making recycled PS flame-resistant are parts around the substrate for an air conditioner, as shown in Fig. 3.

Fig. 3 Example of the parts of a room air conditioner using flame-resistant recycled PS

3.3 Technology for removing contamination from the surface of recycled PP

Regarding contamination of recycled plastics, even a very small amount remaining on the surface can become the starting point of a fracture and deteriorate the impact strength. In addition, if the contamination comes into contact with the surface of molded products, the design will be regarded as inferior. We thought it might be possible to remove the contamination by polishing the surfaces of the flakes. We used the light-colored recycled PP flakes separated as described in Section 3.1 and a dry-friction polisher to polish the surfaces (zero to two times). A specified quantity of antioxidant was added to the flakes for long-term heat-resistance to prepare test samples for evaluation. Table 2 lists the relationship between the area of contamination and the amount of contamination by the number of times of polishing the surface of the light-colored recycled PP. The amount of contamination on

Table 2 Amount of contamination on the recycled PP plate

Contamination area (mm^2) \ Average amount of contamination (pieces)		Number of times of polishing the surface (times) 0	1	2
Invisible domain	<0.05	17	11	9
Visible domain	0.05–0.10	1	0	0
	>0.10	0	0	0
Total contamination in the visible domain (pieces)		1	0	0
Reduction rate of contamination (%)		—	100	100

the test samples (observation area: 7,200 mm^2) was calculated by area while referring to the dirt comparison chart (National Printing Bureau, Japan).

With a larger number of polishing times, the amount of contamination reduced and the contamination area tended to be smaller. Polishing the surface twice could reduce the amount of contamination in the visible domain to zero from one (100%).

Next, Table 3 lists the heat life of light-colored recycled PP. The threshold of the life was determined as 75%[4] of the mechanical property retention (ultimate tensile strength). The long-term heat life at 140ºC was calculated. As the number of times of polishing the surface of light-colored recycled PP increases, the heat life becomes longer, so a clear correlation was seen between the heat life and the amount of contamination. Polishing the surface of recycled PP to remove contamination works well to improve the design and heat life, so we are confident that the method can be applied to exterior parts.

Table 3 Heat life of light-colored recycled PP at 140°C

	Number of times of polishing the surface (times) 0	1	2
Heat life (h)	1,310	1,723	2,295

3.4 Technology for improving the impact strength of recycled PP

The exterior parts for household appliances require sufficient strength to withstand falling impact. A conventional method for improving impact strength is the addition of agents that are highly compatible with PP (e.g., thermoplastic polyolefin (TPO)). We have improved the impact strength using tubes (from daily necessaries) made of low-cost recycled plastics with excellent impact strength. The main component of the tubes is low-density polyethylene (LDPE) and the cost is approximately one-fifth that of TPO (as of June 2017).

To check how the tubes would improve the impact strength, the percentage of tubes to be added was adjusted such that the Charpy impact strength became approximately twofold (140 kJ/m^2) that of recycled PP. The results in Table 4 show that when the additive rate (10 wt%) of the tubes is the same as that of TPO, the Charpy impact strength of recycled PP can be doubled.

Adding tubes for which the main component is LDPE to recycled PP can enhance the impact strength at low cost, so we are confident that the method can be applied to parts requiring impact strength.

Table 4 Impact strength of modified recycled PP

Physical property \ Raw material	Recycled PP	High-impact recycled PP: Tube 10wt% added	TPO 10wt% added
Charpy impact strength (kJ/m^2) (without notch)	70	133	136

4. Conclusion

Mitsubishi Electric has been actively working on closed-loop recycling of plastics collected from discarded household appliances. As a result, we successfully applied closed-loop recycled plastics to our Kirigamine MSZ-Z series of room air conditioner and MR-JX, WX, B, RX, and MX series of refrigerators. We will continue developing material modification technologies for recycled plastics to further increase the quantity of recycled plastics in use.

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