UACJ Technical Reports, Vol.1 (2014), pp. 63-68

論　文

Development of Single Skin Structures which Have an Isotropic High-bending Stiffness*

Masaya Takahashi**

Aluminum honeycomb panels have been used for various industrial applications because of their high-bending stiffness for weight. However, honeycomb panels are too expensive to use in mass production such as automobiles. In order to reduce the manufacturing cost of high-stiffness panels, I have developed single skin structures which are easy to make by sheet metal forming using aluminum sheets. This paper presents the method to create structure patterns which have an isotropic high-bending stiffness. Finite element analyses and experimental tests were conducted in order to investigate the bending behavior of the structures. As a result, it was shown that the developed single skin structures have a high-bending stiffness in any bending orientations and enable more than 50 percent of weight reduction in comparison to a flat sheet under the same bending stiffness conditions.

Keywords: *design, structure, high stiffness, bending stiffness*

1. Introduction

Aluminum honeycomb panels are recognized as lightweight panels with a high-bending stiffness and have been used for various industrial applications since around 1950 [1].

Weight reduction in all products is an important issue in order to build a sustainable society. In particular, the problem of automotive weight reduction is getting more important to improve fuel economy and driving performance. However, the manufacturing cost of honeycomb panels is very high. In order to use high-stiffness panels, such as honeycomb panels, in mass production, it is necessary to reduce the cost of these panels.

Corrugated sheets are used for other conventional high-stiffness panels. Corrugated sheets are commonly used as high-bending stiffness panels in mass production because their manufacturing costs are low. However, there is a problem that these sheets have an anisotropic bending stiffness. In order to solve this problem, I have developed new structure patterns which have an isotropic high-bending stiffness [2].

2. Creation of new high-stiffness structure

Aluminum honeycomb panels consist of two aluminum face sheets and an aluminum honeycomb core and adhesives.

The panels need to be heated in order to bond the face sheets to the core, therefore, the manufacturing cost of the honeycomb panels becomes high.

There are also other high-stiffness panels, corrugated sheets and dimpled sheets. These single skin structures are more suitable for mass production than honeycomb panels, because they are easy to be made by sheet metal forming with a low manufacturing cost.

Corrugated sheets are frequently used as high-stiffness panels in many applications. However, corrugated sheets have an extremely anisotropic bending stiffness, because the second moment of area of the sheet is very high in one direction and very low in the other direction.

Dimpled sheets are another inexpensive type of high-stiffness panels. The bending stiffness of dimpled sheets is about several times higher than that of the flat sheet in any in-plane orientations [3]. There are

* The part of this paper was published in the proceedings of the 12th International Aluminum Conference (INALCO2013), Montreal, Canada, October, 21-25, 2013.

** No. 4 Department, Nagoya Center, Research & Development Division, UACJ Corporation

many concave-convex shapes of dimpled sheets. However, it has not been clarified which optimal concave-convex shapes can maximize the bending stiffness of the sheet.

There are always demands for improving the bending stiffness of a sheet at higher levels than ever before. In various machines and appliances as well as automobiles, there are demands for minimizing the weight of the material to reduce the material cost.

In order to make single skin structures which have a high-bending stiffness in all orientations, I have designed new structure shapes which have a high second moment of area in an arbitrary cross section. In this chapter, I present a method to create these shapes.

Fig. 1 shows a schematic corrugated sheet. The black part is a convex section and the white part is a concave section. **Fig. 2** shows the fundamental region of the schematic corrugated sheet. The fundamental region has an anisotropic bending stiffness. In order to create single skin structures, which have an isotropic high-bending stiffness, I designed a unit pattern using the fundamental region of the corrugated sheet. **Fig. 3** shows the unit pattern which was created by rotating and copying the fundamental region at 90 degree intervals. The structure of the unit pattern could have a high second moment of area in the arbitrary cross sections.

Fig. 4 through **Fig. 6** show continuous patterns which are created by copying the unit pattern. The A-pattern is created by spreading the unit pattern, as shown Fig. 4. The B-pattern is created by putting the unit pattern in the line symmetry, as shown **Fig. 5**. The C-pattern is created by rotating the unit pattern at 90 degree intervals, as shown Fig. 6. Various patterns can be produced using the unit pattern. The concave-convex shapes of these patterns could have a high-bending stiffness in all in-plane orientations, because the arbitrary cross sections of these shapes have a high second moment of area.

3. Finite element analysis

I calculated the bending stiffness of the concave-convex shapes of these patterns using the finite element analysis of a cantilever structure in different bending orientations. **Fig. 7** shows the cantilevers of the A-pattern of which the bending orientations are

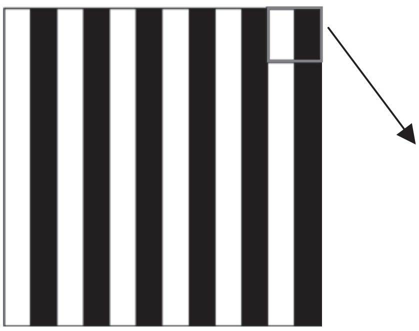


Fig. 1 Corrugated sheet.

Fig. 2 Fundamental region.

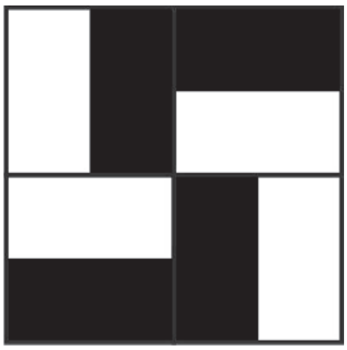


Fig. 3 Unit pattern for isotropic bending stiffness.

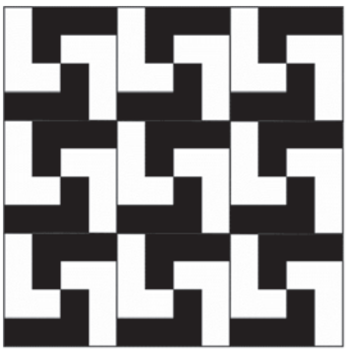


Fig. 4 A-pattern.

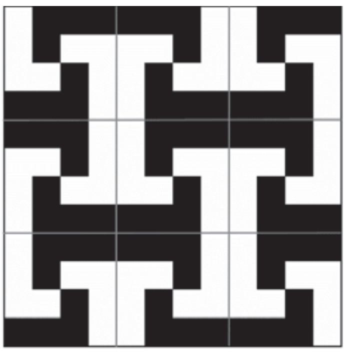


Fig. 5 B-pattern.

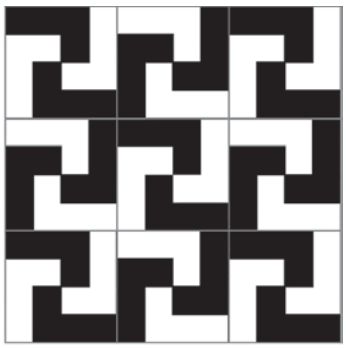
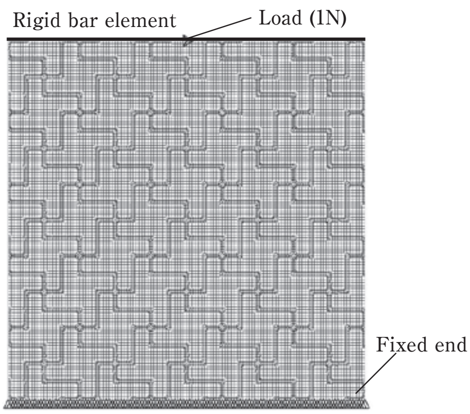


Fig. 6 C-pattern.

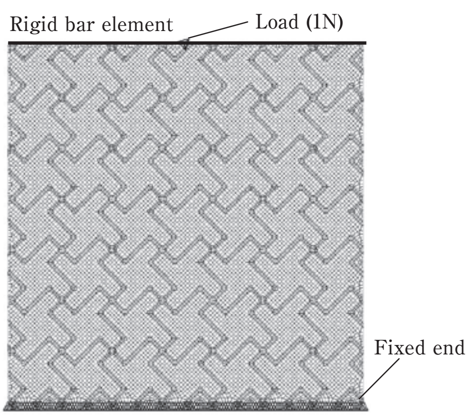
in the 0 and 45 degree directions. These sheet sizes are 120 mm long and 120 mm wide. Finite element analyses were performed in the cases when the bending orientations of the cantilever were changed in directions from 0 to 90 degrees in 15 degree intervals. In the finite element model of the cantilever, the one end of the sheet is fixed, and the other end of the sheet is free. The bending deflections D_f of the free end of the cantilever was calculated when the load F (1 N) was applied. The bending stiffness of the flat sheet S_f was calculated from the bending deflection D_f and the load F as shown in equation (1).

$$S_f = \frac{F}{D_f} \quad (1)$$

The bending stiffness of the concave-convex sheet S_c was calculated from the bending deflection D_c and the load F as shown in equation (2).



(a) Bending orientation of 0 degrees



(b) Bending orientation of 45 degrees

Fig. 7 FE model of cantilever of A-pattern.

$$S_c = \frac{F}{D_c} \quad (2)$$

The relative bending stiffness R is defined in equation (3).

$$R = \frac{S_c}{S_f} = \frac{D_f}{D_c} \quad (3)$$

Fig. 8 shows the dimensions of the unit pattern. The depth of the concave-convex shapes h is 2.0 mm. The depth does not include the thickness of the sheet. The incline angle between the top surface and the side surface θ is 45 degrees. The length of each side of the unit pattern L is 24 mm. A concave-convex shape is formed by sheet metal forming using an aluminum alloy 3004-O sheet whose thickness before forming was 0.3 mm. The volume of the sheet is constant before and after forming. Based on the rate of increase in the surface area, the sheet thickness after forming is determined as follows: the thickness of the A-pattern is 0.265 mm, that of the B-pattern is 0.273 mm and that of the C-pattern is 0.264 mm. For simplicity, I did not consider the thickness distribution.

Fig. 9 shows the bending deflection of the A-pattern, the B-pattern, the C-pattern and the flat sheet with different bending orientations. **Fig. 10** shows the relative bending stiffness of the patterned structures and the flat sheet with different bending orientations. The relative bending stiffness of the A-pattern is 6.7 to 12.1, that of the B-pattern is 10.8 to 16.1 and that of the C-pattern is 8.6 to 9.2.

It turned out that the C-pattern has an extremely

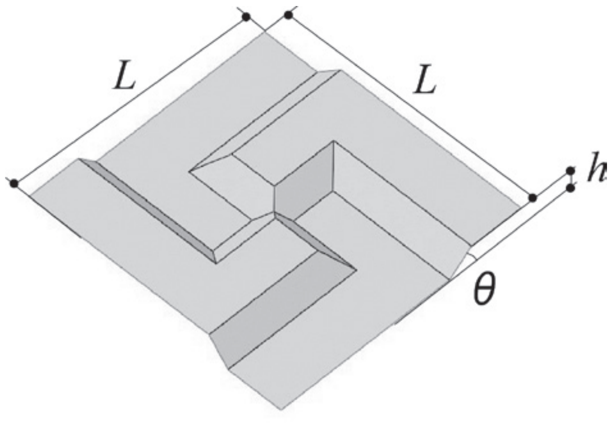


Fig. 8 Dimensions of the unit pattern.

isotropic bending stiffness and the B-pattern has the highest bending stiffness of the three patterns.

4. Approach to increase the bending stiffness

4.1 Creation of improved pattern

I conducted trials to further improve the bending stiffness of the B-pattern by increasing the depth of the concave-convex shape. The B-pattern is not suited to increase the depth of the concave-convex shape because the B-pattern has narrow ribs. Therefore, I changed the shape of the pattern from the B-pattern (Fig. 5) to the D-pattern (**Fig. 11**). The D-pattern has equal width ribs which are suited to increase the depth of the concave-convex shape.

Finite element analyses of the cantilevers of the D-pattern were performed under the same conditions as the B-pattern in order to compare the difference in the bending stiffness between the D-pattern and the B-pattern. As a result, it was found that the bending stiffness of the D-pattern is almost equivalent to that of the B-pattern, as shown in **Fig. 12**.

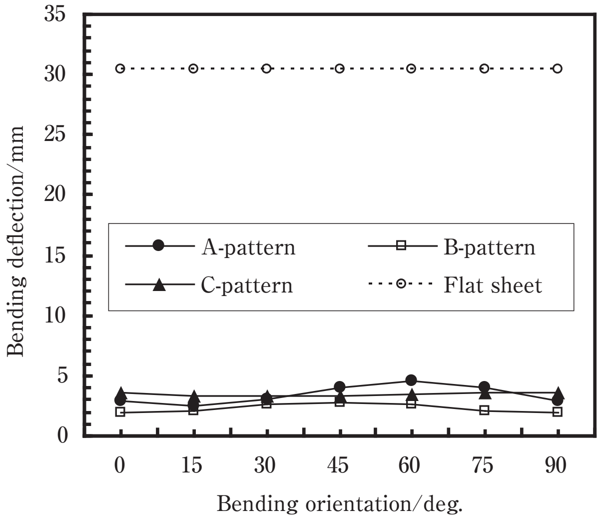


Fig. 9 Comparison of bending deflections between flat sheet and patterned structures.

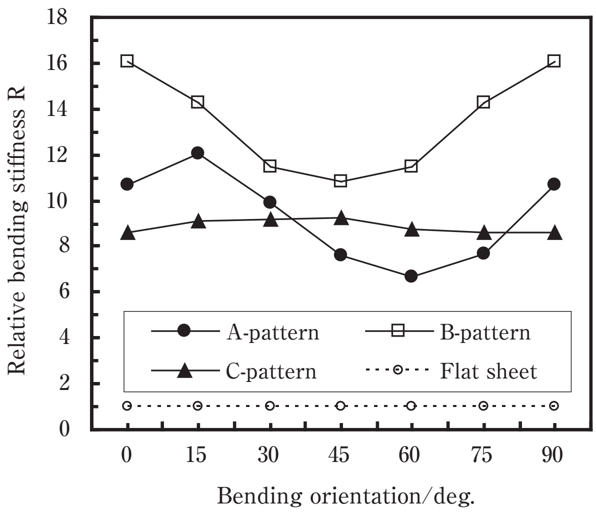


Fig. 10 Comparison of relative bending stiffnesses between the flat sheet and patterned structures.

4.2 Sheet metal forming simulation

The target depth of the D-pattern is 3.0 mm. The depth is 10 times as long as the thickness of the flat sheet before forming. One-step finite element analyses were performed using the concave-convex shape of the unit pattern to investigate the formability during the sheet metal forming. **Fig. 13** shows the finite element model of the sheet metal forming. Only a translation in the vertical direction on the surface is allowed in the nodes of all four edges of the model.

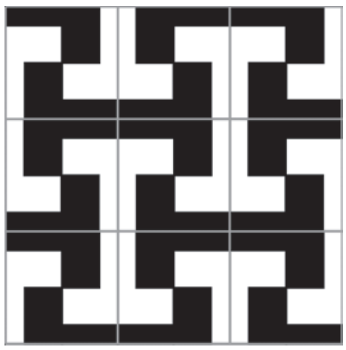


Fig. 11 D-pattern.

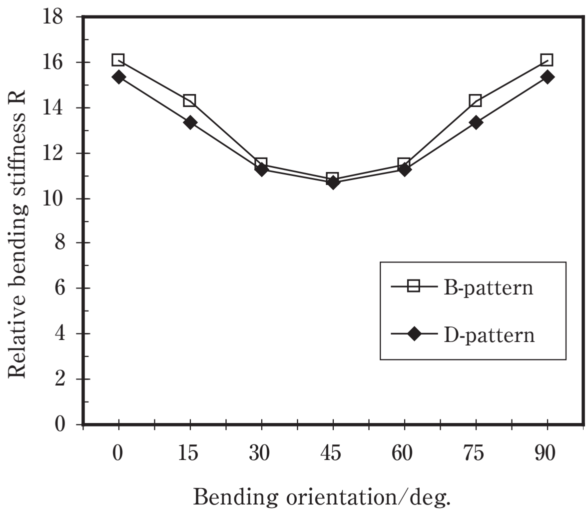


Fig. 12 Comparison of the relative bending stiffnesses between the B-pattern and the D-pattern whose depth are both 2.0 mm.

The stress-strain curve and the forming limit curve for the sheet metal forming are shown in **Fig. 14** and **Fig. 15**. Sheet metal forming simulations were conducted at 30, 45 and 60 degrees in the incline angle. As a result, it is clear that the incline angle of 30 degrees is suitable for the sheet metal forming, because a fracture could occur when the incline angles are 45 and 60 degrees, as shown in **Fig. 16**.

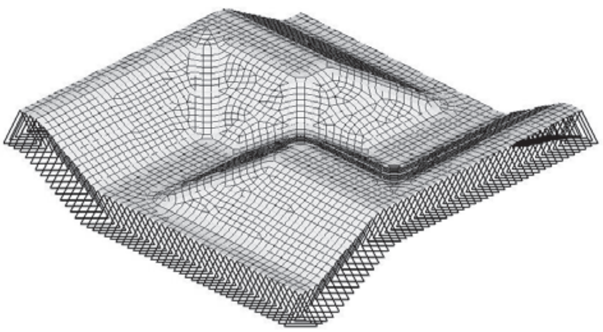


Fig. 13 Finite element model for sheet metal forming.

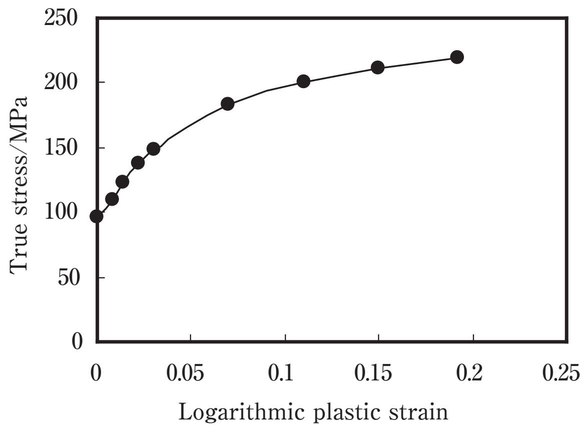


Fig. 14 Stress–strain curve (3004-O).

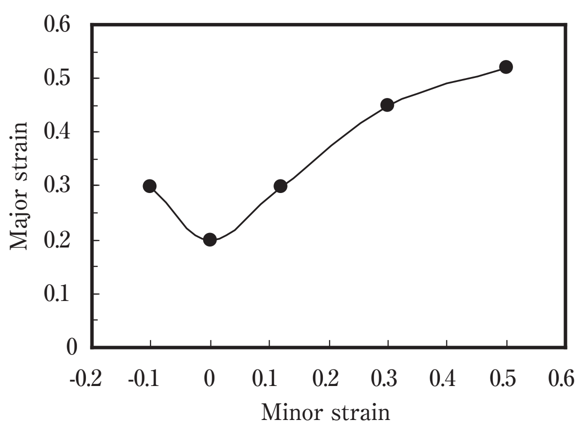
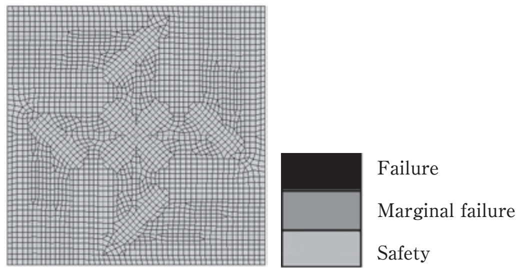


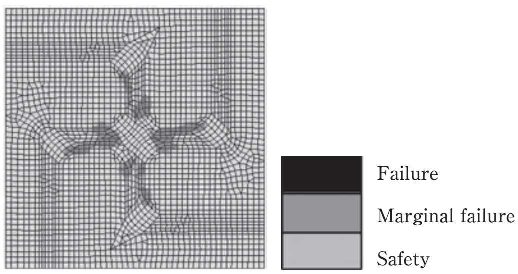
Fig. 15 Forming limit curve (3004-O).

4.3 Three-point bending test

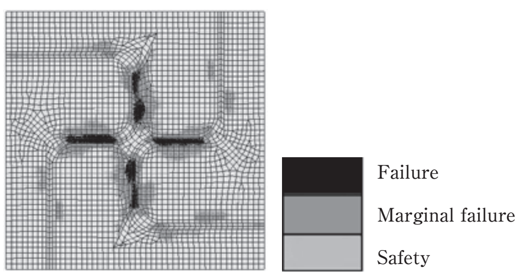
In order to investigate the actual bending stiffness of the D-pattern, I made a concave-convex sheet with the D-pattern by sheet metal forming using the aluminum alloy 3004-O sheet, as shown in **Fig. 17**. **Fig. 18** shows a photograph of the three-point bending test. The specimen, which was 100 mm in width and 100 mm in length, was placed on two supporting pins that were 90 mm apart. The loading force was applied to the middle of the two supporting pins. **Fig. 19** shows a comparison of the load versus deflection curves of the D-patterns whose bending orientations were 0 degrees and 45 degrees. The bending stiffness of the D-pattern was 13.2 N/mm to 22.5 N/mm, and that of the flat sheet was 1.0 N/mm. Hence, the relative bending stiffness R was 13.2 to 22.5.



(a) Inclineangle of 30 degrees



(b) Inclineangle of 45 degrees



(c) Inclineangle of 60 degrees

Fig. 16 Simulation results of sheet metal forming.

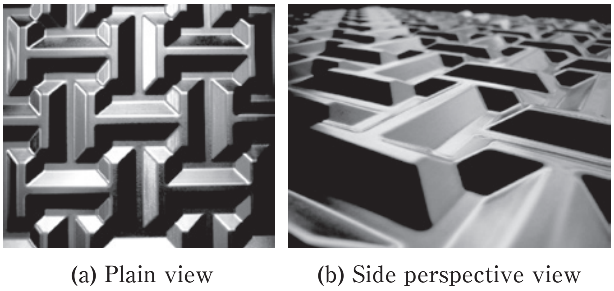


Fig. 17 Concave-convex sheet of D-pattern.

Fig. 18 Three-point bending test.

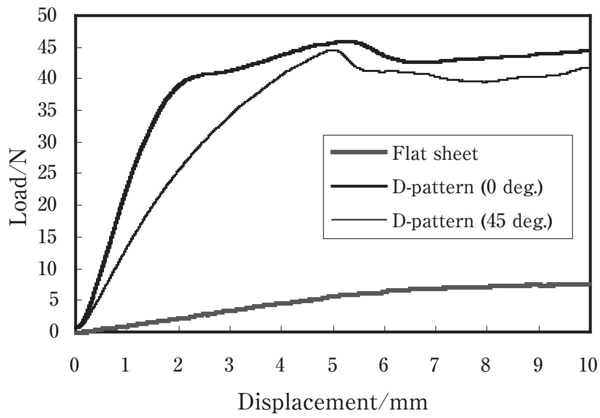


Fig. 19 Load-displacement curves of three-point bending test.

The weight reduction ratio W is expressed as a function of the relative bending stiffness R, which is defined in equation (4).

$$W(\%)=\left(1-\left(\frac{1}{\sqrt[3]{R}}\right)\right)\times 100 \qquad (4)$$

Fig. 20 shows the relation between the relative bending stiffness R and weight reduction ratio W. The concave-convex sheets with the D-pattern could provide a weight reduction of more than 57 percent in comparison to a flat sheet under the same bending stiffness condition.

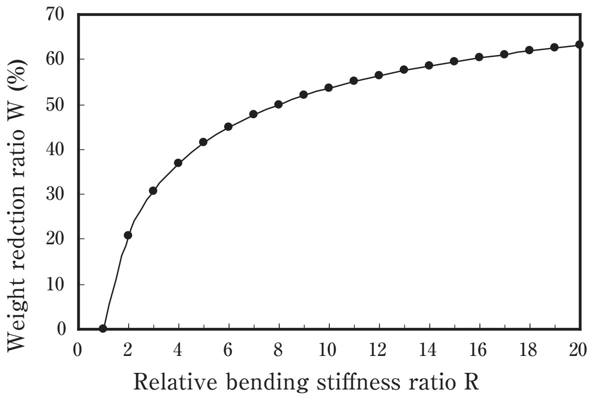


Fig. 20 Relation between relative bending stiffness and weight reduction ratio.

5. Conclusion

In various machines and appliances, there is a demand for improving the bending stiffness of the sheet material to higher levels. In order to solve this problem, I have developed new single skin structures which have an isotropic bending stiffness. Finite element analyses and experimental results showed that the single skin structures could halve the weight of flat sheet under the same bending stiffness conditions.

References

1) T. Bitzer: Honeycomb Technology, Chapman and Hall, (1997), 2.
2) M. Takahashi: Transactions of the Japan Society of Mechanical Engineers, Series A, **77** (2011), 1410-1416.
3) F. Mirtsch, N. Weinert, M. Pech and G. Seliger: Proceedings of the 13th CIRP International Conference of Life Cycle Engineering, (2006), 630-634.

Masaya Takahashi
No. 4 Department, Nagoya Center, Research & Development Division, UACJ Corporation