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Composite Material for Automotive Headliners —Expandable Stampable Sheet with Light Weight and High Stiffness—†

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Abstract:

KP Sheet is a stampable sheet made of glass fiber (GF) and polypropylene (PP), and has a distinctive characteristic of expansion in thickness. To realize light weight and high stiffness in automotive headliners, the GF content and arrangement in the thickness direction were studied with the aim of increasing expansivity. Although expansivity increases with GF content and the elastic slope is enhanced by the resulting increase in sheet thickness, the maximum elastic slope reaches saturation at a GF content of 50 mass% or more. Therefore, the GF arrangement in the thickness direction is controlled to improve GF spring back, resulting in a 30% improvement in expansivity at the same unit weight. A newly-developed ultra-light product (UL grade) realizes a high elastic slope of 7.2 N/mm at a web unit weight of 800 g/m², while also displaying excellent moldability and dimensional stability equal to those of normal grade KP Sheet, enabling further weight reduction.

1. Introduction

To improve marketplace competitiveness, automobiles are equipped with a full range of convenience and safety devices such as car navigation systems, back view monitors, and air bags. On the other hand, as means of reducing environmental loads, weight reduction in automotive parts and improved engine fuel consumption are also under study. Against this background, fiber reinforced composites, which possess high specific strength and specific stiffness, have drawn attention as materials responding to the need for weight reduction.

K-Plasheet, which is a member of the JFE Steel Group, produces and sells fiber reinforced composites for press forming use (stampable sheet “KP Sheet”) made of glass fiber (GF) and polypropylene (PP). They have won an excellent evaluation from customers for their light weight, formability, and low coefficient of thermal expansion. Since 1997, they have been widely adopted in automotive interior parts, and particularly as headliner materials, as shown in **Photo 1**.

Broadly classified, three types of headliner material have been used in recent years: (1) stampable sheet made of GF and PP, such as KP Sheet, (2) GF laminated polyurethane foam, generally called polyurethane sandwich headliner (substrate), which consists of a GF mat laminated with polyurethane foam on both sides, and

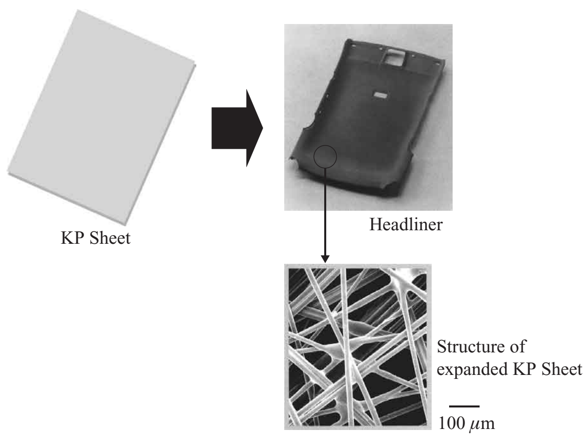

Photo 1 Headliner made of KP Sheet

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(3) thermoplastic foam.[1,2]

The features required to headliner materials include (1) low release of harmful chemicals and foul odors in the process of molding headliner parts from material in order to improve the workplace environment, (2) high handling stiffness during installation in the auto assembly process, (3) light weight and minimal dimensional change in parts in environmental atmospheres, high durability, and high sound absorption, and (4) good recyclability when the automobile is scrapped.

Because KP Sheet is made of PP, no harmful chemicals or foul odors are released in the molding process, and as reheating is possible, it also has recyclability. As shown in Photo 1, when KP Sheet is molded to produce a headliner, its microstructure forms a porous structure in which PP fixes the intersection points between glass fibers. Dimensional change in the product is slight because GF suppresses shape change due to molding shrinkage and environmental heat loads, and durability is excellent. In addition, the product is also sound absorbent, which is a distinctive feature of its porous structure.[3]

This paper presents the results of a study of stiffness improvement in the development of a new type of KP Sheet with lighter weight and enhanced stiffness, and introduces UL grade (ultra-light grade), which was newly developed based on the study results.

2. Features of KP Sheet and Design of Lightweight Material

2.1 Production Method

KP Sheet for automotive headliners, as shown in **Fig. 1**, has a laminated structure consisting of an olefin film, which is applied on one side of a stampable sheet and is used in attaching the surface texture and securing non-permeability, and a PET scrim applied to the reverse side. The KP Sheet production process comprises a papermaking process, pressing process, and shearing/finishing process. In the papermaking process, a mat-like intermediate product called web is obtained by uniformly dispersing GF and PP in a foamy slurry, followed by continuous papermaking, as in the conventional papermaking. In the pressing process, the web is laminated with a film or spanboard and pressed to form a sheet. The sheets are then sheared and finished for delivery to the customer.[4]

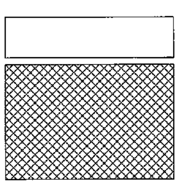

Fig. 1 Schematic illustration of KP Sheet for automotive headliner

2.2 Features of KP Sheet

The most important feature of the KP Sheet is its expansivity. GF is accumulated not only in a 2-dimensional plane, but also in the thickness direction; in other words, GF has a 3-dimensional arrangement. This structure is the basic reason for the high expansivity which is an advantage of the KP Sheet. In the pressing process, the accumulated GF is compressed into a sheet in a state with residual stress. The KP Sheet used in automotive headliners is generally processed by a molding method called expansion molding. In the customer's molding process, the KP Sheet is first heated in an infrared oven or an other type of heating furnace. When the PP melts, the residual stress is released, and the entire sheet expands due to spring back of the GF. Since the PP is in a molten state at this time, the GF structure has a degree of freedom to deformation, and the sheet manifests excellent formability together with expansion. If the expanded KP Sheet is molded in a die with a clearance, a molded product with a thickness 2–4 times that of the original sheet can easily be obtained, making it possible to manufacture large parts with high stiffness.[5] Moreover, it is also possible to apply a surface texture to form a sheet in a single process by laminating the film on the expanded sheet.

2.3 Design of Lightweight Material

To reduce weight while maintaining stiffness, it is necessary to increase the original stiffness of the material. It is generally known that stiffness is proportional to the product (EI) of elastic modulus (E) and the second moment of area (I). This means that stiffness can be improved by various methods which increase the elastic modulus, or the second moment of area (i.e., increase the product thickness). As mentioned in the previous section, the KP Sheet has an advantage of expanding when heated due to GF spring back. Since this feature also makes it possible to increase I, high rigidity can be obtained with the same unit weight.

In the process of expansion molding, the distribution of PP in the sheet changes from that in the KP Sheet production process, as illustrated in **Fig. 2**. Specifically, in the web stage, particles of PP (powder form) are held between the glass fibers. Since the PP melts and becomes fluid during pressing, the glass fibers are covered with PP in the sheet stage. When the sheet is heated in the customer's manufacturing process, the PP melts again and is pulled and dispersed by the GF as the distance between glass fibers increases due to spring back,

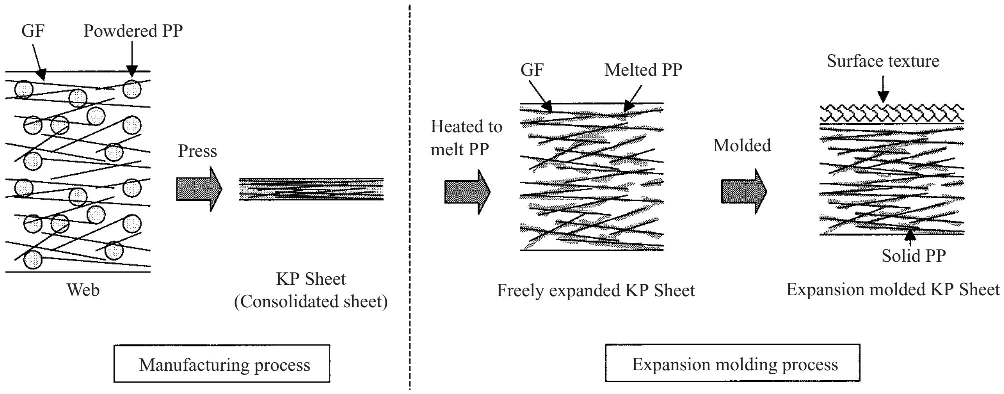

Fig. 2 Change in distribution of PP in manufacturing and expansion molding processes

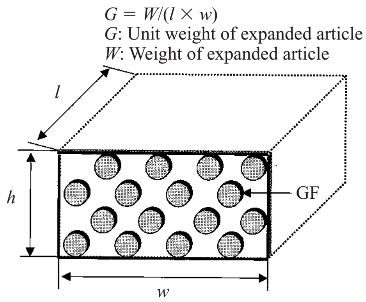

Fig. 3 Schematic model of expanded article of KP Sheet

causing PP to concentrate around the glass fibers and at GF intersection points. Even if the KP Sheet is compressed into a certain thickness during stamping, only a small part of the PP coalesces. The larger part remains distributed around the GF and at GF intersections in the same dispersed distribution.

Since unit weight (per unit of area) and thickness are considered to contribute to rigidity, a model of an expansion-molded material consisting mainly of GF was used, as shown in **Fig. 3**. Assuming that GF is uniformly distributed in an arbitrary cross-section, and therefore the number of glass fibers per unit of cross-sectional area is also uniform, the second moment of area can be expressed by the following equation:

$$I = w \cdot A \cdot n \cdot h^3 / 12 \quad \cdots\cdots (1)$$

where,

w : Width (mm)
h : Thickness (mm)
A : Cross-sectional area of GF (mm^2)
N : Number of glass fibers in arbitrary cross-section

Using the unit weight and GF content of the expansion-molded material, the value of $A \cdot n$ can be expressed as follows:

$$A \cdot n = (GC / h) / \rho \quad \cdots\cdots (2)$$

where,

G : Unit weight of expansion-molded material (g/mm^2)
C : GF content (mass%)
ρ : Density of glass (g/mm^2)

For a given GF content, the strength of the GF intersections bonded by PP is constant, irrespective of the compression ratio (molded thickness/expanded thickness). In other words, assuming the elastic modulus of the GF intersections is constant, EI is proportional to the second moment of area (I). Accordingly, using Eqs. (1) and (2), EI is proportional to the product of the unit weight and second power of the thickness, as expressed by the following equation:

$$EI \propto (wC / \rho) \times G \times h^2 \quad \cdots\cdots (3)$$

From this equation, it can be understood that unit weight can be reduced if it is possible to increase the thickness of the expansion-molded KP Sheet. To increase thickness, it is necessary to increase the expanded thickness by increasing the effect of GF spring back.

Therefore, the effect of the molded thickness and unit weight on stiffness, that of the arrangement of GF in the thickness direction on the expanded thickness, and that of PP distribution attributable to the increase in expanded thickness on stiffness were investigated, and a new ultra-light weight, high stiffness material was developed based on the knowledge obtained.

3. Experimental Procedure

3.1 Preparation of KP Sheet Samples

The PP powder and GF (length: 25 mm) were dispersed in a slurry, and papermaking was performed to produce sample materials of 250 × 250 mm in size. They were dried at 180°C to produce web with unit weights of 635 to 800 g/m^2. GF contents of 45, 50, 55, and 60 mass% were used. Pressing was performed at a pressure of 0.3 MPa for 15 s at 205°C with an olefin film laminated on one side of the web and a PET scrim on the other. The pressed material was cooled and solidified to produce sheets.

In addition, web with a controlled GF arrangement was pressed to sheets using web produced by papermaking at K-Plasheet.

3.2 Preparation of Expanded Sheets

The expanded sheets were prepared by two methods. The first was a free-expansion method in which the KP Sheet was placed on a Teflon sheet and heated to 200°C in a far-infrared oven, then allowed to expand freely. Without cooling the material, the sheet was transferred to a room temperature die and molding was performed. The expanded sheets were also allowed to cool without molding, and the sheet thickness was measured and used as the free expansion thickness. In the second method, the sheet was expanded between hot press plates with a clearance of either 3.5 mm or 5 mm. The samples were then transferred to a room temperature die without cooling, and molding was performed. The expanded sheet produced by expansion with the 3.5 mm clearance followed by molding was called restricted expansion sheet. Since the maximum expanded thickness did not reach 5 mm, the sheet produced by expansion with the 5 mm clearance and molding was called free expansion sheet.

3.3 Bending Test

The test pieces of l 150 × w 50 mm were cut from the expanded sheets for the bending test. The crosshead speed in the bending test was 50 mm/min, and the fulcrum spacing was 100 mm. Loading was applied to an olefin film surface. Stiffness was evaluated from the elastic slope, which was obtained from the initial inclination of the load-deflection curve in the bending test.

3.4 Observation of Cross-Section

The arrangement of GF in the thickness direction was observed using the soft X-ray radiography of the cross-section. For observation of the PP distribution, test pieces were cut from the expanded sheet, embedded in epoxy resin, and finished by polishing. The PP was then observed in an optical microscope.

4. Results and Discussion

4.1 Effects of Expansion Molded Thickness and Unit Weight on Stiffness

Figure 4 shows the relationship between the expansion molded thickness and the elastic slope of the sheet

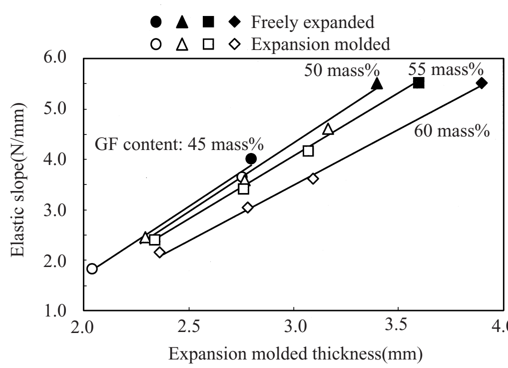

Fig.4 Effect of GF content and expansion molded thickness on elastic slope (Unit weight of web: 635 g/m²)

with a web unit weight of 635 g/m². For all GF contents, the value of the elastic slope increased with the molded thickness. On the other hand, for the same molded thickness, the elastic slope increased as the GF content decreased. However, for a GF content of 45 mass%, spring back was weak due to a small number of GF fibers, and expansion was limited to only 2.8 mm. For this reason, the maximum value of the elastic slope which could be obtained was 4 N/mm. In contrast, as the GF content was increased, spring back also increased and expansivity improved. At the GF content of 50 mass%, the free expansion thickness reached 3.4 mm, and the elastic slope increased to 5.5 N/mm. At 55 mass% and higher, GF spring back increased further, resulting in an additional increase in the free expansion thickness, but the maximum value of the elastic slope had leveled off saturation. Thus, the minimum GF content for obtaining the maximum elastic slope is 50 mass%.

Next, to investigate the effect of unit weight, an experiment was performed in the same manner with the GF content set for 50 mass% and the web unit weight increased to 700 g/m². **Figure 5** shows the results, together with those for a unit weight of 635 g/m², arranged by GF unit weight × (thickness)² as in the relationship in Eq. (3). The elastic slope and GF unit

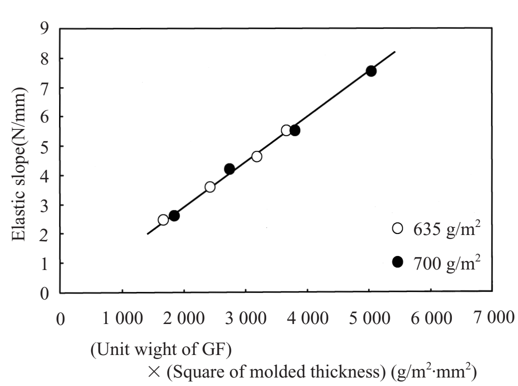

Fig.5 Effect of the product of square of expansion molded thickness and unit weight of GF on elastic slope (GF content: 50 mass%)

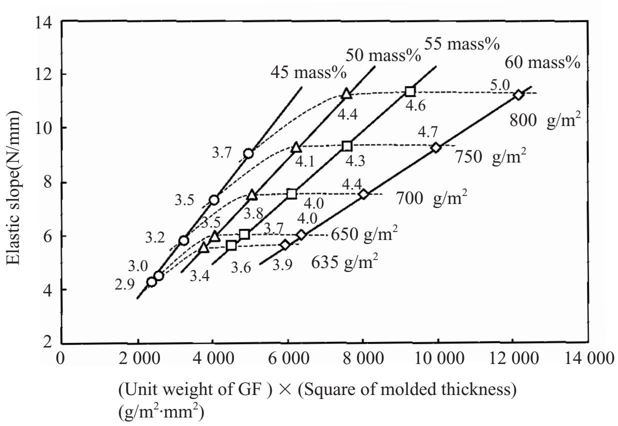

Fig. 6 Relationship between Elastic slope and the product of unit weight of GF and square molded thickness

weight × (thickness)^2 are proportional, and the results for 635 g/m^2 and 700 g/m^2 fall on the same line. Based on this, it is possible to compensate for a reduction in unit weight by increasing the expanded thickness. Therefore, if the expansivity of 635 g/m^2 material can be improved, the same elastic slope as with 700 g/m^2 can be expected.

To study this relationship in more detail, an experiment was performed with various unit weights up to 800 g/m^2. **Figure 6** shows the relationship between the free expansion thickness (i.e., maximum expanded thickness) and elastic slope under each set of conditions, arranged by GF unit weight × (thickness)^2. The numerical values in the figure are the free expansion thickness. As with Fig. 5, Fig. 6 shows that it is also possible to arrange the elastic slope by GF unit weight × (thickness)^2 with different unit weights. Furthermore, as the GF content increases, the slope of the straight line decreases, and it becomes difficult to increase the elastic slope by increasing thickness. Regarding the effect of the GF content, as with the results obtained for 635 g/m^2 (Fig. 4), the elastic slope becomes leveled off at GF contents of more than 50 mass%, even when the unit weight is increased. This means that the minimum GF content for obtaining the maximum elastic slope at a constant web unit weight is 50 mass%.

Therefore, the authors investigated the arrangement of GF at a GF content of 50 mass% with the aim of enhancing the elastic slope.

4.2 Effect of GF Arrangement on Free Expansion Thickness

Web is formed by defoaming the material slurry in a papermaking machine and accumulating a mixture of GF and PP on the forming belt, as shown in **Fig. 7**. Because the accumulating angle θ is considered to influence the arrangement of GF in the thickness direction, web with

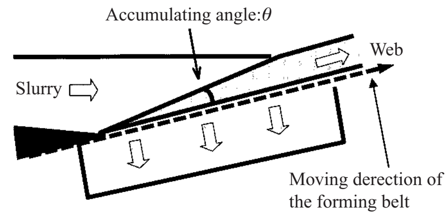

Fig. 7 Schematic diagram of the papermaking machine

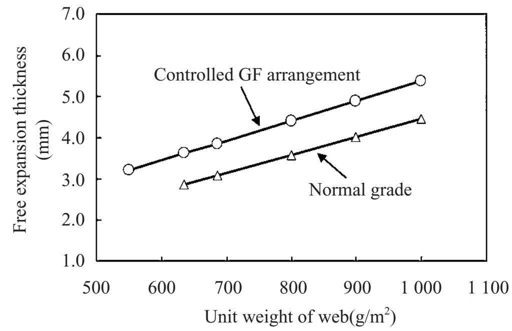

Fig. 8 Comparison in free expansion thickness between controlled GF arrangement and normal grade

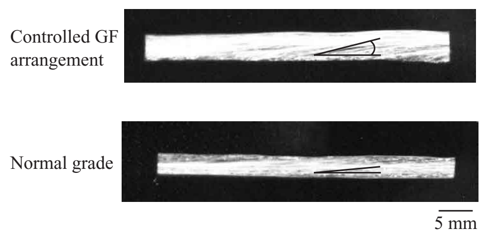

Photo 2 GF arrangement in thickness direction of expanded KP Sheet (Unit weight of web: 900 g/m^2)

multiple unit weights was produced while controlling the accumulating angle in order to study the effect on the free expansion thickness. The results are shown in **Fig. 8** in comparison with the normal material, arranged by the web unit weight. By controlling the accumulating angle, it was possible to increase the free expansion thickness by 30% in comparison with the normal grade.

To investigate the arrangement of GF in the expanded sheets, cross-sections were observed by soft X-ray radiography using test pieces with a web unit weight of 900 g/m^2. The results are shown in **Photo 2**. It can be understood that the accumulating angle is increased by arranging GF in the thickness direction. As a result, it is considered that the spring back effect during heating is greater and the free expansion thickness increases.

The above has described the results when molding was performed after free expansion based on the hypothesis in Eq. (3). Next, the authors examined the effect of the expanded thickness on the elastic slope.

4.3 Effect of Expanded Thickness on Stiffness

An experiment was performed using press plates with a clearance to limit expansion to the clearance gap.

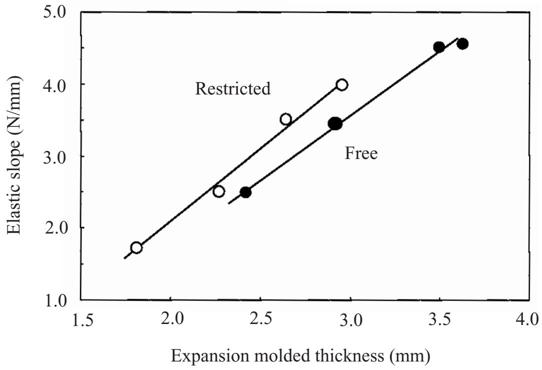

Fig. 9 Comparison in elastic slope between restricted and free expansions (Unit weight of web: 800 g/m^2, GF50 mass% Web: Controlled GF arrangement)

The web with a unit weight of 800 g/m^2, GF content of 50 mass%, and controlled accumulating angle was used. **Figure 9** shows the elastic slope of this material plotted against the expansion molded thickness. The molded thickness of the free expansion material showed a maximum of 3.6 mm, while that of the restricted expansion material was 2.9 mm. When the elastic slope was compared at the same 2.9 mm, which was the molded thickness, a high value of 4 N/mm was obtained with the restricted expansion material, in contrast to 3.4 N/mm with the free expansion material. However, when the absolute maximum values were compared, the free expansion material achieved a higher value of 4.5 N/mm, in contrast to 4 N/mm with restricted expansion, demonstrating the effect of increased thickness. Considered in terms of Eq. (3), because the GF content is identical, the same elastic slope should be obtained with the same thickness. However, the results do not show this. To study this difference between restricted expansion and free expansion materials, the PP distribution was compared by observing cross-sections of test pieces with an elastic slope of 3.5 N/mm. The results are shown in **Photo 3**. The white areas are PP, and other areas are voids. The PP in the restricted expansion product forms a continuous material, whereas the PP in the free expansion product has separated into discrete areas. It is therefore thought that, in free expansion, the molten PP lacks sufficient elongation and separates as the distance between glass fibers increases with thickness. Accordingly, it may be inferred that the strength of the GF intersections differs in the two types of material when compared at the same thickness. Although the elastic slope is reduced by separation of PP in the free expansion material, it is possible to offset this reduction if an adequate expansion molded thickness can be achieved. Based on this fact, when attempting to improve stiffness by increasing the molded thickness, it is necessary to increase the molded thickness sufficiently to exceed the reduction in the elastic slope caused by PP separation during expansion. Moreover, it can also be understood that, when there are restrictions on the molded thickness, it is possible to form continuous PP by limiting the expanded thickness.

In the foregoing, the effects of GF content, unit weight, molded thickness, and expanded thickness on stiffness were studied using a model of expansion molded KP Sheet, and their respective contributions were clarified. However, because weight reduction is required with the material in practical applications, there is limitation on unit weight. It is possible to compensate for unit weight by increasing the GF content and molded thickness. The molded thickness can be increased by controlling the arrangement of GF and increasing the expanded thickness. However, it is necessary to increase the molded thickness sufficiently to offset the reduction in stiffness caused by PP separation during expansion.

Based on these results, an ultra-light weight, high stiffness material (UL grade) was developed by optimizing the respective factors.

4.4 Features of Developed Material (UL Grade)

In the developed material (UL grade), a GF content of 50 mass% is used and expansivity is enhanced by controlling the GF arrangement. The elastic slope of the UL grade was evaluated, as shown in **Fig. 10**, which summarizes the values of the elastic slope for various

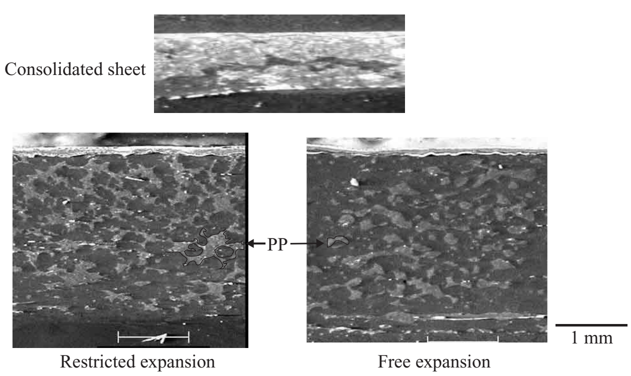

Photo 3 Distribution of PP in expansion-molded articles

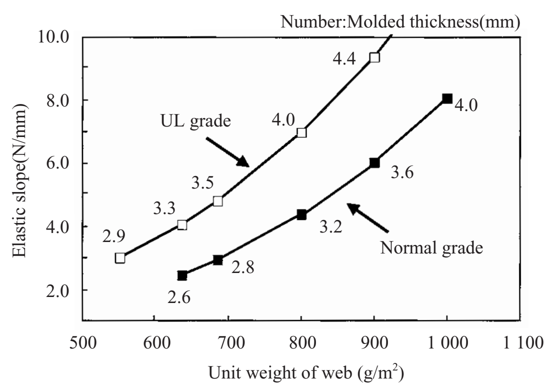

Fig. 10 Comparison in elastic slope between UL grade and normal grade

unit weights. The numerical values in the figure are for the molded thickness. When compared at the same unit weight, the developed material shows a 50% improvement in elastic slope in comparison with the normal grade. Conversely, at the same elastic slope, a 20% weight reduction is possible. Thus, the developed UL grade is an outstanding material for either improving the stiffness performance of parts or for reducing part weight.

5. Conclusion

To meet requirements for light weight and high stiffness in automotive parts, JFE Steel and its subsidiary K-Plasheet succeeded in improving the stiffness of KP Sheet for automotive headliners by controlling the GF arrangement of the material and optimizing expansivity and PP distribution, and developed and commercialized a new ultra-light KP Sheet (UL grade) with improved stiffness. The developed material has the following outstanding features:

(1) In the UL grade, free expansion was improved by 30% in comparison with the normal grade. As a result, the second moment of area is increased and stiffness is improved by 50%.

(2) With the same stiffness, a 20% weight reduction is possible.

A product with excellent sound absorption is under study, taking advantage of the porosity which is a feature of the expanded material, and development of materials with further improved functions is planned.

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