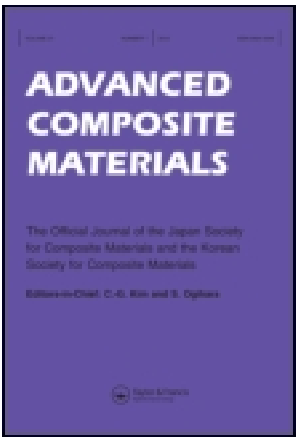

Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

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Version of record first published: 02 Apr 2012.

To cite this article: T. Katayama , M. Shinohara , M. Hakotani & M. Toutani (2002): Development of the CAE system to predict stiffness of a SMC structure: research on the Young's modulus in the rib part , Advanced Composite Materials, 11:1, 95-103

To link to this article: http://dx.doi.org/10.1163/156855102753613327

Adv. Composite Mater., Vol. 11, No. 1, pp. 95–103 (2002)

Development of the CAE system to predict stiffness of a SMC structure: research on the Young's modulus in the rib part

T. KATAYAMA [1], M. SHINOHARA [2], M. HAKOTANI [3] and M. TOUTANI [1,*]

[1] *Department of Mechanical Engineering, Doshisha University, Totara-toya, Kyo-Tanabe City, Kyoto 610-0321, Japan*

[2] *Department of Mechanical Engineering, Maizuru National College of Technology, Japan*

[3] *Research Laboratory, Takeda Chemical Industries Ltd., Japan*

Abstract—Sheet Molding Compound (SMC) products often have ribs to improve the stiffness of the structures. However, even with the ribs, the expected stiffness may not be attained. In these cases, the die design must be changed, which involves great cost. Therefore, a CAE system to predict the stiffness to improve efficiency of the die design is needed.

Structure analysis is used in the stiffness prediction, for which a knowledge of Young's modulus is required. We aim to construct a method for the calculation of Young's modulus in the rib part of a SMC product. In this study, the effect of the flow channel geometry and reinforced fiber length on Young's modulus in the rib part was investigated.

From the results, we could show the effect of the flow channel geometry on fiber weight content and orientation in the rib part. However, we could not show the effect of the reinforced fiber length.

Keywords: SMC; compression molding; CAE; products with rib; prediction of stiffness.

1. INTRODUCTION

Sheet Molding Compound (SMC) has been widely applied in industry for diverse uses, such as automotive exterior parts and housing facilities, because of its excellent mechanical properties, relatively low cost, lightweight, and good design possibilities.

Typical SMC products often have ribs in order to reduce the weight of the structures without loss of stiffness. However, in these products, various problems such as sink mark, weld lines, warpage and heat cracks often occur. These problems are caused by the complexity of fiber distribution and fiber orientation. In such cases, it is necessary to change the design of the mould. However, it is very costly

*To whom correspondence should be addressed.

to do so, since the die for compression molding of SMC, which must be able to endure the molding in high temperature and high pressure, is very expensive. It needs further expenditure of time to change the design after making the die. So, a CAE system is needed to improve the efficiency of mold design, and we are trying to construct such a CAE system to predict the stiffness of structure in SMC compression molding.

In previous studies, structure analysis has been used in the stiffness prediction and, for this, a knowledge of Young's modulus is required. Since material flow in SMC is complicated and unsteady, and this is even more complicated in the rib part, it is difficult to estimate the conditions of material flow, fiber distribution, fiber orientation, and so on. So, an effective approach would be to apply a database that is systematically arranged by these various factors.

The SMC structural member is divided into the flat plate part, of which the material flow is not so complicated, and the rib part, for which the material flow is very complicated. Then we have predicted the Young's modulus of each part. We can predict Young's modulus in the flat plate part by simulation (flow analysis, fiber orientation analysis) and using the database. In the rib part, it is possible to predict Young's modulus according to the database that shows the relationship between Young's modulus and B/ts in correlation with the flow [1] (Here, B/ts is the ratio between rib width B and material thickness ts as the material passes the rib in the molding process.). However, the relationship between flow channel geometry and Young's modulus in the rib part is not clear. And the relationship between flow channel geometry and reinforced fiber length also is not clear because only fiber length, which is 1 inch, served as an object.

In this paper, we investigate the effect of flow channel geometry and reinforced fiber length on Young's modulus in the rib part. Specifically, we investigate fiber distribution, fiber orientation and Young's modulus in the rib part.

2. THE BASIC RESEARCH ON YOUNG'S MODULUS IN RIB PART

2.1. Molding method

Products were molded by using the press machine for FRP compression molding. There is a rib in the center part of the die. It is possible to change rib width B to 2, 3, 4, 5, 10, 20 mm and rib height H to 10, 20, 30, 40 mm.

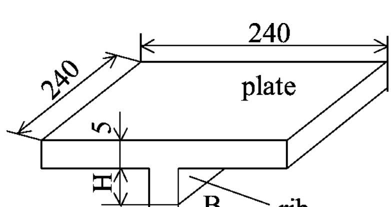

Figure 1. Shape of products.

Products were molded in the shape of a letter T, as shown in Fig. 1, on 100% charge pattern. Here, charge pattern represents the ratio of material area to the whole die area. The closing speed was set at 0.15 mm/s and the die pressure at 5 MPa for all shapes of the rib. The die temperature of the upper and lower die was maintained at 140°C.

In this experiment, the reinforced fiber lengths L of the SMC material were 1 and 2/3 inch, respectively. The contents of the SMC are shown in Table 1.

2.2. Material flow and fiber orientation in the rib part

Soft X-ray photographs were taken from the side of the rib on $B = 2, 3, 4, 5, 10,$ 20 mm. The test pieces were cut off from the central part of the rib to prevent edge effects.

Figure 2 shows the soft X-ray photograph in the case of $H = 30$, $B = 2$ mm, $L = 1$ inch. From this photograph, it is observed that the proportion of the resin-rich part increases with the decrease of the rib width. It is considered that glass fibers were bound in the upper part of the rib, and then the resin was pressed out into the lower portion of the rib when the material flows into the rib part. It is proven that fibers relatively tend to orientate in the longitudinal direction of rib part in the region over the resin-rich layer, and in the transverse direction of that in the upper layer.

2.3. Fiber weight content in the rib part

2.3.1. Experimental method. The test pieces were made by dividing into the height direction of the rib at every 5 mm as shown in Fig. 3 with $B = 2, 3, 4, 5,$ 10, 20 mm, $H = 30$, 40 mm and $L = 1, 2/3$ inch, and the measuring of fiber weight content was carried out. In this experiment, the ratio B/ts was used as the parameter that showed the geometry of die. Here, it is proven that B/ts had the large correlation with material flow in the past research.

Table 1.
Contents of SMC

Resin	25.0 wt%
Glass fibre	22.0 wt%
$CaCO_3$	53.0 wt%

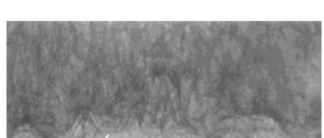

Figure 2. Soft X-ray photograph ($B = 2$, $H = 30$, $L = 1$).

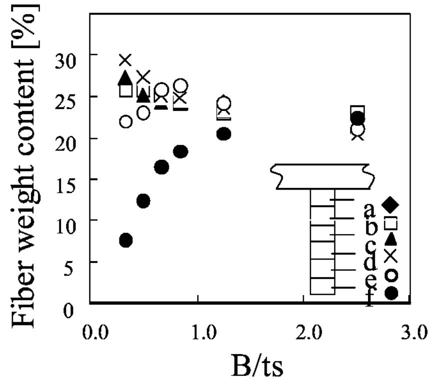

Figure 3. The relationship between B/ts and fiber weight content ($H = 30$, $L = 1$).

2.3.2. Results and discussion. The relationship between fiber weight content and B/ts in the case of $H = 30$ mm, $L = 1$ inch is shown in Fig. 3. From this result, as B/ts is larger to some extent, fiber weight content in each region is almost constant, which is the SMC raw material of 22 wt% in all experimental molding conditions. In the meantime, as B/ts is smaller to some extent, fiber weight content decreases in the lower layer of the rib part in all conditions. However, it increases in the upper and middle layer. It is considered that the gelled resin in the upper and middle layer was pressed out into the lower portion of the rib, when the material flows into the rib part.

2.4. Young's modulus in the rib part

2.4.1. Experimental method. The tensile test was carried out by the application of JIS K7054 by using an Instron universal test machine of 4206 type. The test pieces were made by dividing into the height direction of the rib at every 5 mm with $B = 2, 3, 4, 5, 10, 20$ mm, $H = 10, 20, 30$ mm and $L = 1, 2/3$ inch as shown in Fig. 3. The tensile test was carried out in the longitudinal direction of the rib.

2.4.2. Results and discussion. The relationship between Young's modulus and B/ts in the case of $H = 30$, $L = 1$ inch is shown in Fig. 4. In all conditions, as B/ts is increased, Young's modulus is almost constant and Young's modulus in the rib part can be expressed by using B/ts. However, as B/ts is decreased, in each region dispersion of Young's modulus occurs and hence its value in the rib part cannot be expressed by using B/ts. As an apparent consequence of the dispersion, it may be mentioned that in the rib bottom the Young's modulus is extremely low because the region is resin-rich.

3. RESEARCH ON YOUNG'S MODULUS IN THE RIB PART

In Sections 2–4, the rib becomes heterogeneous in all molding conditions, as B/ts decreases. But the heterogeneity is largely divided into two, with one region being

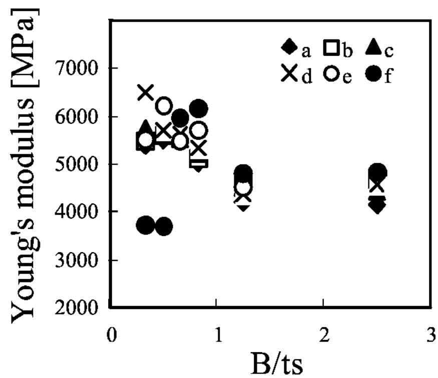

Figure 4. The relationship between B/ts and Young's modulus ($H = 30$, $L = 1$).

resin-rich. If there is a database that shows the changes in size and Young's modulus of each region with molding condition it is possible to predict a Young's modulus in the heterogeneous rib part. So the rib part was divided and the effect of the molding condition on each region was investigated.

3.1. The method to divide the rib part

The resin-rich region is one in which the fiber weight content is smaller than the other part of the product. It should be possible that the resin-rich region can be investigated with the soft X-ray photograph and expressed in terms of glass fiber weight content. However, it is impossible to express the correspondence of stiffness, since factors such as the fiber orientation complicate the situation.

So we defined that Young's modulus of the resin-rich region is under an appropriate Young's modulus [1] as resin-rich. Its Young's modulus is 3700 MPa. The test pieces of 2, 4, 6 mm height from rib bottom were made and the tensile test was carried out. Therefore we defined H_R as the height of the resin-rich region from the bottom of the rib.

The other region was divided into two parts equally, because the Young's modulus differs in the upper and lower region a little in Fig. 4.

3.2. The effect of molding condition on resin-rich region

In Section 3.1, the Young's modulus in the resin-rich region is defined 3700 MPa. Therefore it is important to investigate how H_R changes with molding condition.

The relationship between H_R and B/ts in the case of $H = 30$ mm, $L = 1, 2/3$ inch is shown in Fig. 5. From the result, it is proven that H_R increases with the decrease of B/ts in case of each fiber length. H_R is almost same, as rib height is 30, 40 (mm).

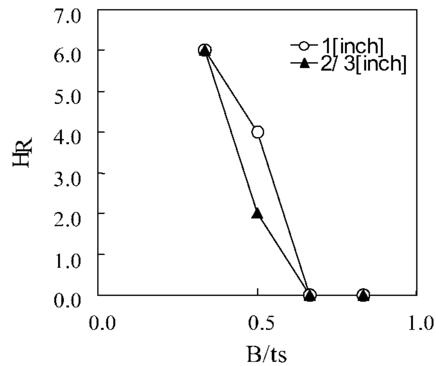

Figure 5. The relationship between B/ts and H_R ($H = 30$).

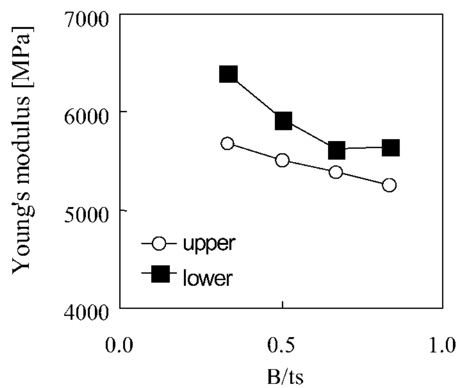

Figure 6. The relationship between B/ts and Young's modulus ($H = 30$, $L = 1$).

3.3. The effect of molding condition on the other region

The relationship between Young's modulus in the other region and B/ts in the case of $H = 30$, $L = 1$ inch is shown in Fig. 6. It is proven that Young's modulus in the other region increases with decrease of B/ts in all conditions.

The relationship between Young's modulus in the other region and H in the case of $L = 1$ inch is shown in Fig. 7. It is proven that the Young's modulus in the other region decreases, as the rib height increase from 30 to 40 mm.

3.4. Research on fiber orientation in the non-resin-rich region

In Section 3.3, it was proven that Young's modulus was affected by B/ts and rib height. From this reason, it is considered that the fiber orientation and fiber weight content would also chang with B/ts and rib height. So fiber orientation in the non-resin-rich region was investigated.

3.4.1. Experimental method. The rib width is very thin. Therefore, the two-dimensional plane between rib height direction and longitudinal direction was

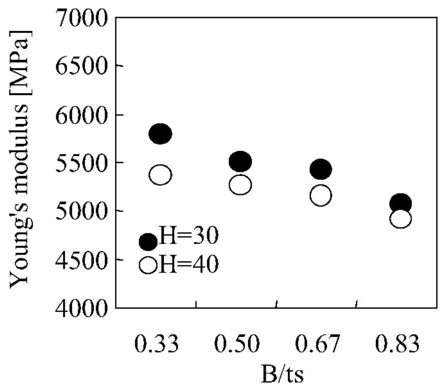

Figure 7. The relationship between B/ts and Young's modulus ($L = 1$).

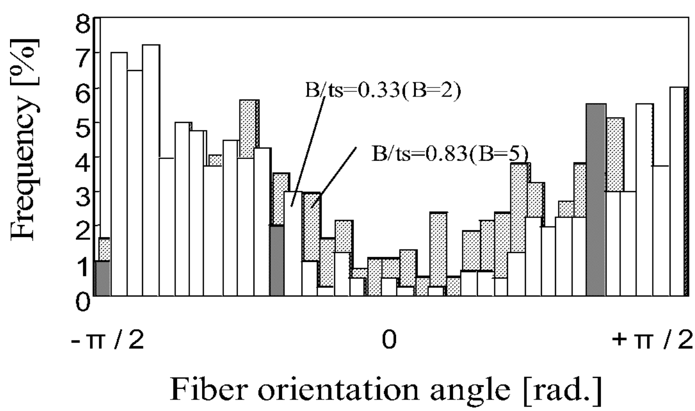

Figure 8. The orientation characteristic ($H = 30$, $L = 2/3$).

investigated. The rib width was divided equally into 4 regions and each cross-section was investigated in one rib; after which the results were superimposed. To obtain the general tendency, the fiber orientation in the case of $B = 2$, 5 mm, $H = 30, 40$ mm, $L = 1, 2/3$ inch was investigated.

3.4.2. The fiber orientation characteristics. The fiber orientation distribution in the case of $H = 30$ mm, $L = 2/3$ inch is shown in Fig. 8. In this figure, 0 rad shows the orientation in the longitudinal direction of the rib part; $+\pi/2$ and $-\pi/2$ rad shows respectively the orientation in the upper and lower direction of the rib height. By investigating the fiber orientation characteristics, it is proven that as B/ts decreases, fiber orientates in the flow direction, which is approximately $\pm\pi/2$ rad. For this reason, it is considered that as the rib width decreases, the velocity gradient of the inflow direction increases by the reduction in flow. Furthermore, the fiber orientates to the flow direction which is approximately $\pm\pi/2$ rad.

Because the proportion of the longitudinal fiber is lower in Fig. 8, Young's modulus seems to become lower, as rib width is smaller. However, this effect

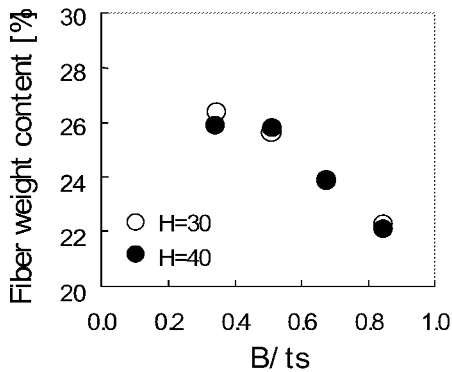

Figure 9. The relationship between B/ts and fiber weight content ($L = 1$).

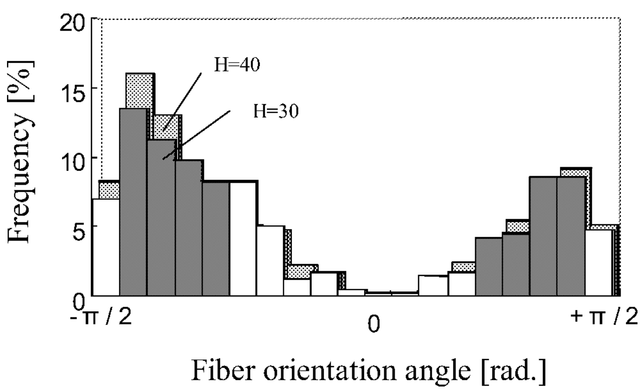

Figure 10. The orientation characteristic ($B = 2$, $L = 2/3$).

is not seen in Fig. 6. For this reason, it is considered that fiber weight content influences Young's modulus. So fiber weight content in the non-resin-rich region is investigated and the result is shown in Fig. 9. In this figure, the fiber weight content is higher, as rib width is smaller. From these results, it is confirmed that both fiber orientation and fiber weight content, which are changed over the rib width, influence Young's modulus in the heterogeneous rib.

By investigating the fiber orientation characteristics, it is proven that the proportion of the fiber which orientates at approximately $\pm\pi/2$ [rad.] increases a little, as rib height increases. The fiber orientation distribution in the case of $H = 30$, 40 mm, $L = 2/3$ inch is shown in Fig. 10. For this reason, it is considered that as the rib height increases, the flow distance is lengthened and the fiber is turned into the inflow direction.

From Fig. 7, the Young's modulus in the other region decreases a little as rib height H increases. And from Fig. 9 the fiber weight content in the non-resin-rich region is almost the same, even if the rib height changes. From these results, it is confirmed that it is not fiber weight content but fiber orientation change with rib height that influences the value of Young's modulus in the heterogeneous rib.

4. CONCLUSIONS

(1) The size of resin-rich region is greatly affected by B/ts. However, it is hardly affected by rib height or fiber length.

(2) Young's modulus in the non-resin-rich region is affected by rib width and rib height. However, we could not confirm the effect of the fiber length.

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