3.2. Improved treatment between first and second step

In order to overcome the problems of our final products in Sec. 3.1, we have proposed an improved method not with cutting the plane bamboo sheet separately like in the previous method (Fig. 10) but by jointing parts as shown in Fig. 11. This improved sheet, which is an expansion pre-press sheet with a jointing part, makes it feasible to set and control the relative position in arranging them, as shown in Fig. 12, and in hot press forming them on the mold die surface. Moreover, we attempt to mold a thick bamboo fiber sheet with double the weight (from 20 g/sheet to 40 g/sheet) instead of eight piece sheets in Fig. 8 and predict that this method would make it possible to generate fewer gaps and cracks between the cutting places except the jointing parts of an expansion pre-press sheet.

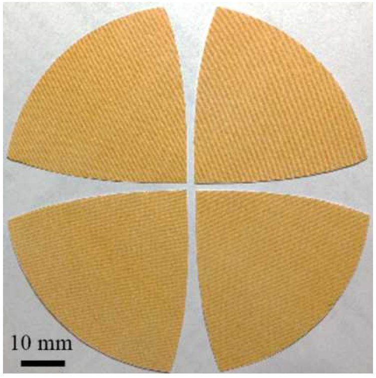

Fig. 10 Initial method method (cutting bamboo sheet separately)

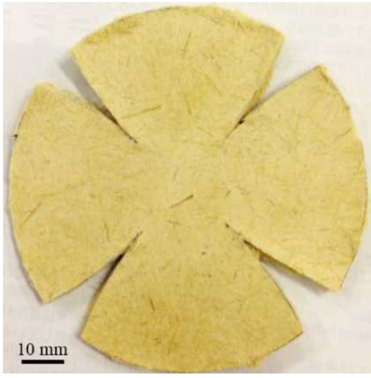

Fig. 11 Improved method (cutting the sheet with jointing a part)

Fig. 12 Bamboo fiber plane sheet after fitting in mold die

Fig. 13 Bamboo hemisphere shell shape product with improved method

Table 4 Improvement of efficiency in molding time

	Initial method [min.]	Developed method [min.]
Drying and weighing bamboo fiber	15	15
Hot press forming (plane shape)	10x2 (2 sheets)	10 (1 sheet)
Cooling time (plane shape)	30x2 (2 sheets)	30 (1 sheet)
Time of cutting bamboo fiber sheet and arranging it into the mold	2x2 + 6 (2 sheets + arranging time)	2
Hot press forming time (hemisphere shell shape)	10	10
Cooling time (hemisphere shell shape)	30	30
Total hot forming time	145	97

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Figure 13 shows one of our final products using the novel improved method. The novel bamboo fiber product could form the hemisphere shell shape much better without almost any cracks or gaps between the cutting joints. Furthermore, we can see no jointing line on the surface, as shown by arrows in Fig. 9. It also significantly reduces the molding time and increases fabricating efficiency as shown in Table 4, compared with the initial method. Here, hot press forming time and cooling time at the first step forming are kept constant simply because they are considered to be unessential, compared with the second step forming.

3.3. Suitable treatment between first and second step

The improved treatment is found to be effective to maintain the product's quality and to reduce the fabricating time. However, the jointing area was determined by a trial and error method. Therefore, we need to discuss the jointing diameter 2a in Figs. 14 and 15 to obtain the proper performance of our final product. If the distance 2a is too short, this could cause the bamboo fiber sheet to break when we put it into the mold and might cause cracks or gaps in the product as in the initial method in Sec. 3.1. Besides, if $2a$ is too long, it could be more difficult to put the bamboo sheet into the mold, might cause exceedingly unequal distribution of bamboo fiber inside the mold and consequently might reduce the final product quality. Basically, the limited deformation of pre-press sheet is considered an essential factor under the bamboo fiber press molding process condition. That is, its variation in volume is considered one of the important factors between before and after the press molding process.

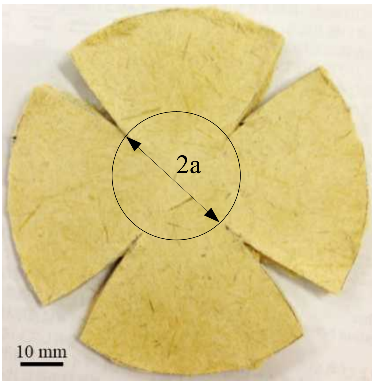

Fig. 14 A part of jointing area (medium-size product)

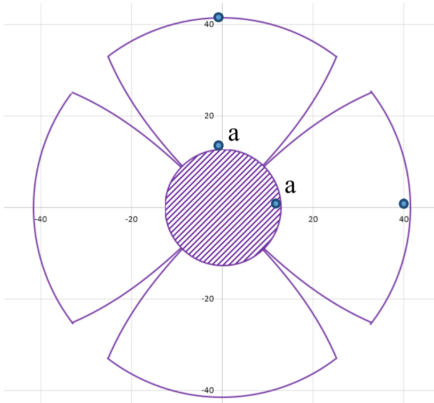

Fig. 15 Definition of dimension based on a circular model

Therefore, we focus on the difference in volume between the circular plate and the hemisphere shell as a criterion in the industrial press molding field. Here, we consider a model to calculate an adequate distance 2a in Figs. 14 and 15, based on two variables which are the plane sheet's thickness h and the spherical radius R of the product. Comparing the volume of the circular plate in Fig. 16 (b) with one of its hemisphere shell in Fig. 16 (c), we discuss the influence of distance $2a$ on the quality of the press molded product. As mentioned in Sec 2.2, less flow performance and less plastic zone is essential at the second step forming. Thus, we focus on a geometrically different value as a simplified criterion to determine the $2a$ value.

Here, the volume of the plane circle part (Fig. 16 (b)) is calculated as:

$$V_{plane} = \pi a^2 h \tag{1}$$

Where a is the radius of the circle and h is the plane sheet's thickness after pre-press molding, as shown in Fig. 16 and Fig. 17. Besides, the volume of this circular part varies with the hemisphere shell when it is fit on the mold die:

$$V_{spherical} = V_1 - V_2 = \frac{2\pi R^2 k_1}{3} - \frac{2\pi(\mathrm{R}-h)^2 k_2}{3} \tag{2}$$

Where R is the spherical radius of the hemisphere shell
V_1, V_2 are volumes of the spherical sector with a radius of R and R-h relatively,
k_1, $k_2$are height values of spherical cap of V_1, V_2

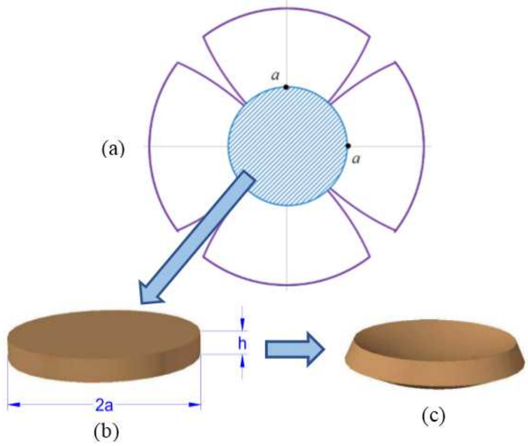

Fig. 16 Circular part before and after fitting on hemisphere shell mold die surface

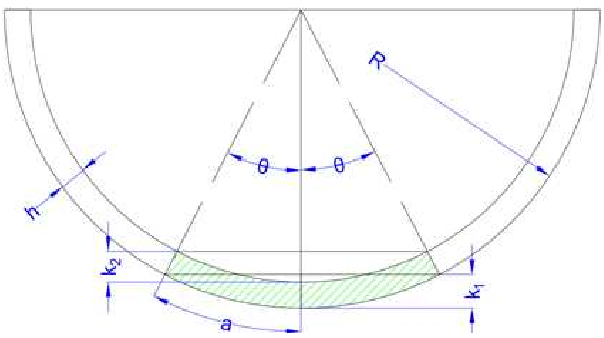

Fig. 17 Diagram of the bowl's cross section

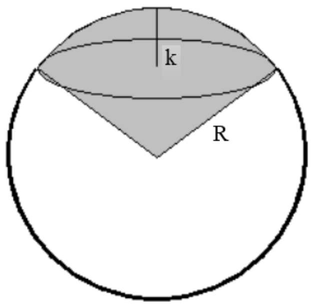

Fig. 18 Spherical sector

While $V = \dfrac{2\pi R^2 k}{3}$ is the geometric equation to calculate the volume of the spherical sector with radius R and the height k of the spherical cap (as shown in Fig. 18)
h is assumed to be the same after second step hot press molding because the sheet is already pressed in the first step. While k_1, k_2 (as shown in Fig. 17) can be calculated as follows:

$$\begin{aligned} k_1 &= R\left(1-\cos\theta\right) \\ k_2 &= \left(R-h\right)\left(1-\cos\theta\right) \end{aligned} \tag{3}$$

$$\text{While } \theta = \frac{a}{R}$$

$$\therefore V_{spherical} = \frac{2\pi}{3}\left(1-\cos\frac{a}{R}\right)\left(R^3-\left(R-h\right)^3\right) \tag{4}$$

That is, we discuss the difference between the volume of plane circular part V_{plane} and volume of the spherical shape $V_{spherical}$ based on the quality performance of our final product. In general, the relative error ε is considered one of the important factors to discuss the relative variation between two values. Therefore, we look at the relative difference defined as Eq. (5):

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$$\varepsilon = \frac{V_{plane} - V_{spherical}}{V_{spherical}} = \frac{V_{plane}}{V_{spherical}} - 1 \tag{5}$$

Here, by substituting Eq. (1) and Eq. (4) to Eq. (5), we have Eq. (6):

$$\varepsilon = \frac{\pi a^2 h}{\frac{2\pi}{3}\left(1-\cos\frac{a}{R}\right)\left(R^3-(R-h)^3\right)} - 1$$

$$\therefore\ \varepsilon = \frac{a^2 h}{\frac{2}{3}\left(1-\cos\frac{a}{R}\right)\left(R^3-(R-h)^3\right)} - 1 \tag{6}$$

From Eq. (6), it can be seen that the value of ratio ε depends on radius a, thickness h, and spherical radius R. In the present report, all three kinds of our products have the same spherical radius R = 40 mm (outer-side).Thus we attempt to determine the general value of ε based on experimental results, and from that value and thickness h, we can calculate the suitable a for each product.

3.4. Discussion and case study based on suitable treatment between first and second step

First, we experimented on a small-size product with a bamboo fiber weight of 35 g as shown in Fig. 19. Because the radius of this product is quite small, we have estimated two kinds of products with a= 16 and 22 mm from the viewpoint of a jointing line on the product surface. Here, in the case of a= 22 mm, we do not need to cut the bamboo fiber sheet because it is equal to the sheet's radius. These are ε=8.9% and 10.2%, respectively. It can be seen in Fig. 19 that there is almost no difference between the two products. As a result, the expansion of pre-press sheet is found to be needless under around ε = 10% of the relative volume variation before and after second hot press molding.

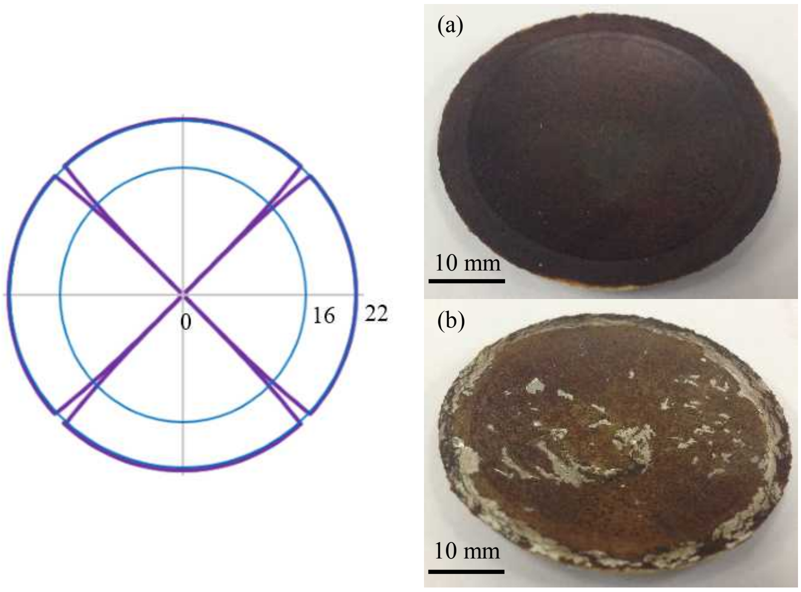

Fig. 19 Small-size products with (a) ε= 8.9%, (b) ε=10.2% (no cutting)

Second, with the medium-size product and bamboo fiber weight of 30 g as shown in Fig. 20, we have estimated three kinds of products with a=16, 24 and 32 mm, which are ε = 7.8%, 9.6% and 12.2% , respectively. The products with a = 16 and 24 mm have almost no difference in Fig. 20 (a) and (b), just as shown in Fig. 19. But the product with a = 32 mm does not have as good cohesion at the jointing parts in Fig. 20 (c). It is considered that the jointed parts in the expansion pre-press sheet prevent one from gluing the outer parts. Therefore, with this size of product, the products with *a* = 16 and 24 mm can have the good performance in terms of product cohesion. As a result, the jointing part of the pre-press expansion sheet is also found out to be suitable under around ε = 10% of the relative volume variation before and after second hot press molding.

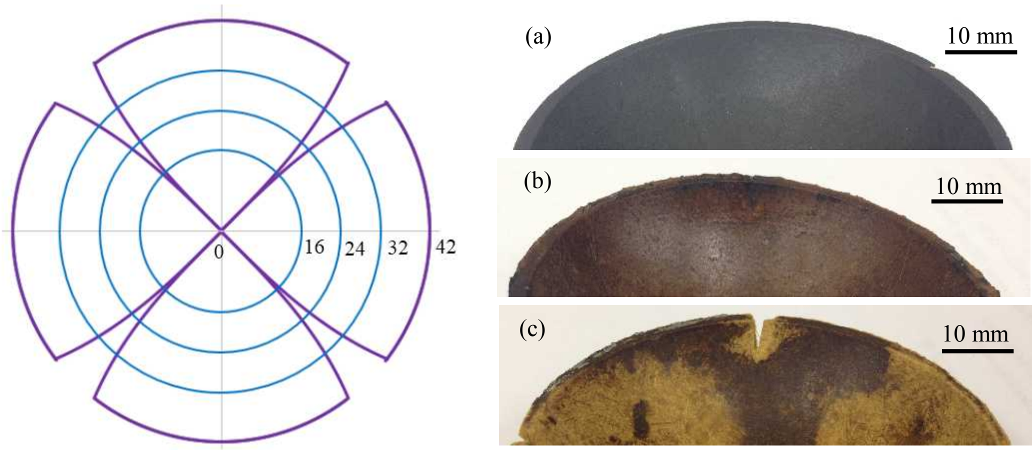

Fig. 20 Medium-size products with (a), (b), (c) are ε = 7.8%, 9.6% and 12.2%, respectively

Regarding the large-size product and bamboo fiber weight of 30 g as shown in Fig. 21, the estimations for three values of *a* =16, 24 and 32 mm have been carried out, which are ε= 7.8%, 9.6% and 12.2%, respectively. Because this kind of product has the largest size, it is considered difficult to mold the pre-press sheet. Consequently, with the product of *a* = 16 mm, we can see small cracks or gaps at the outer part of product because *a* is too small to make the bamboo fiber sheet stick together when second hot press molding, as shown in Fig. 21 (a). Besides, regarding the product of *a* = 32 mm, the jointed parts in the expansion pre-press sheet prevent it from gluing the outer parts, and we can see the broken line at the outer part, as shown in Fig. 21 (c). Compared with them, we can have good cohesion in the case of *a* = 24 mm, as shown in Fig. 21 (b). Finally, regarding this size of product, the product with *a* = 24 mm could give us the most acceptable quality and its equivalent value of ε is also 9.6%.

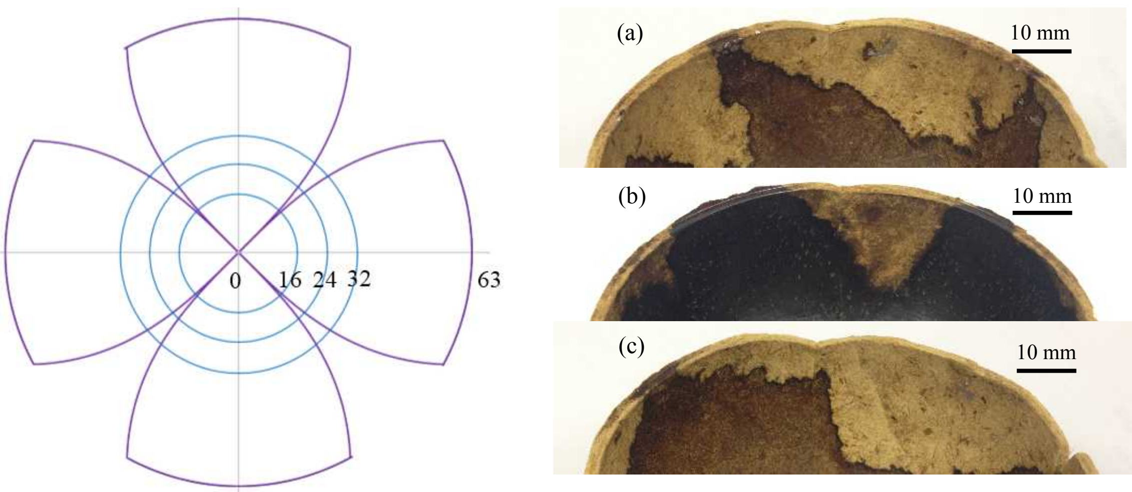

Fig. 21 Large-size products with (a), (b), (c) are ε= 7.8%, 9.6% and 12.2%, respectively

From these experimental results, it can be seen that around ε=10% should be kept for the good cohesion performance in our final products. Therefore, ε=10% is considered a general criterion in the industrial press molding field and we can select the suitable value of *a* derived from Eq. (6) for each product in Fig. 2.

Here, we attempt to estimate the influence of ε value on a mechanical property such as the strength of the product. Figure 22 shows the set-up of three-point bending test in the case of a medium-size product. Two edges of hemisphere shell are set on the side of the cylindrical supporting bar, the load is set at the top of the hemisphere shell and the jointed line is located at the center of supporting bar, as shown in Fig. 22. Figure 23 shows the obtained curves relationship between the displacement at the loaded point and the mounted load. The solid line curve and broken line indicate the first result and the second one at each ε value, respectively. It can be seen that the load at breaking indicates the maximum value at ε=9.6% such as around ε=10%. The same tendency is obtained in the case of the other size products.

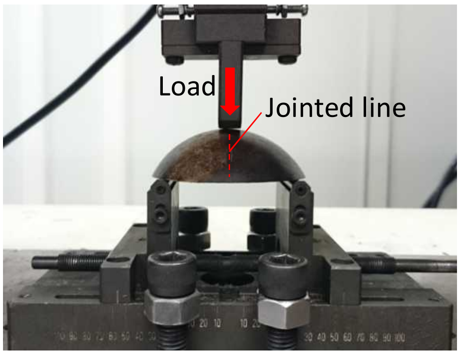

Fig. 22 Set-up of bending test (Medium-size product)

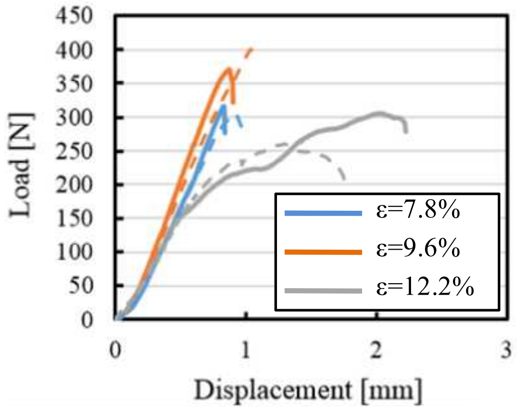

Fig. 23 Results of bending test (Medium-size product)

As a result, it is demonstrated that the relative volume variation between the expansion sheets and product shell shape is an essential factor to generate the fine press molding shell product made of pure 100% bamboo fibers at the suitable treatment between the first and second step in Fig. 6. The pieces of the expansion sheet in Fig. 15 need to be connected at the area under the relative volume variation 10% to fabricate the fine shell products in the treatment between first and second step.

3.5. Stress distribution in second step hot press molding

Finally, we attempt to simulate the stress distribution in molding process of all three sizes of product by Solidworks Simulation in Solidworks software to investigate the effect of stress value around the areas of ε=10%. In this simulation, we focus on the static stress after forming the hemisphere shell in the molding die as shown in Fig. 24.

We used the static structural analysis system which is used for linear material in our simulation. We set the mold material as stainless steel and bamboo fiber sheet material as bamboo fiber with properties as shown in Table 6. Next, we applied the same force F = 14.7kN in Table 3 onto the top surface of the upper mold die for each product and the fixed surface is the bottom surface of the mold die, as shown in Fig. 24 (a). Besides, we used the standard automatic meshing function in the software with the element size of 7.5 mm to create the high-quality mesh shown in Fig. 24 (b). Component contact, a no-penetration type with friction coefficient 0.3, is the surface between the bamboo fiber product and the mold die. That is, we set a standard friction coefficient value between the fine steel surface and the woody material surface. Boundary and simulating conditions are also presented in Table 5. The estimated stress distributions are shown in Fig. 26, 27 and 28.

Table 5 Boundary and simulating conditions

Analysis type	Static
Mesh type	Solid Mesh (Standard mesher of Solidworks)
Contact type	No penetration
Coefficient of Friction	0.3
Applied force [kN]	14.7
Fixture	Bottom surface of the mold
Stress type	von Mises Stress

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Table 6 Material properties in simulation

	Bamboo Fiber	Cast Stainless Steel
Model type	Linear Elastic Isotropic	Linear Elastic Isotropic
Elastic Modulus [GPa]	5.88	190
Tensile Strength [MPa]	10.3	-
Poisson's Ratio [N/A]	0.25	0.26
Mass Density [kg/m^3]	560	7700
Yield Strength [MPa]	80	-
Shear Modulus [GPa]	-	790

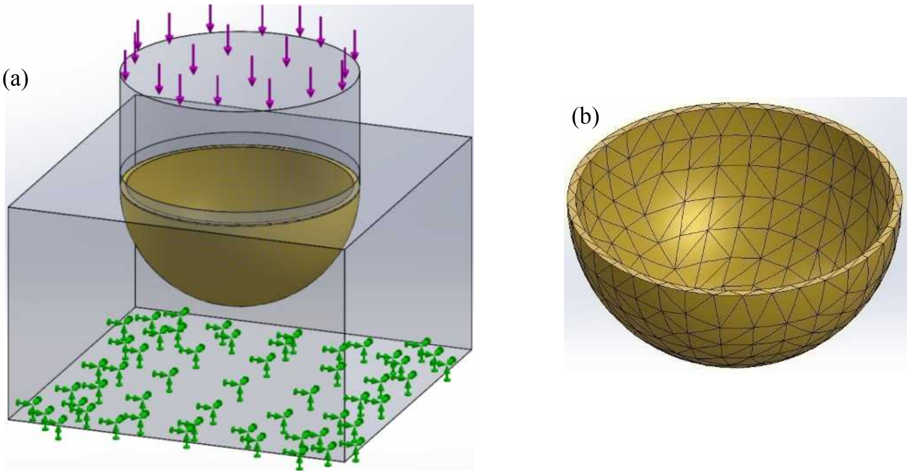

Fig. 24 Simulation process and meshed product in case of large-size product

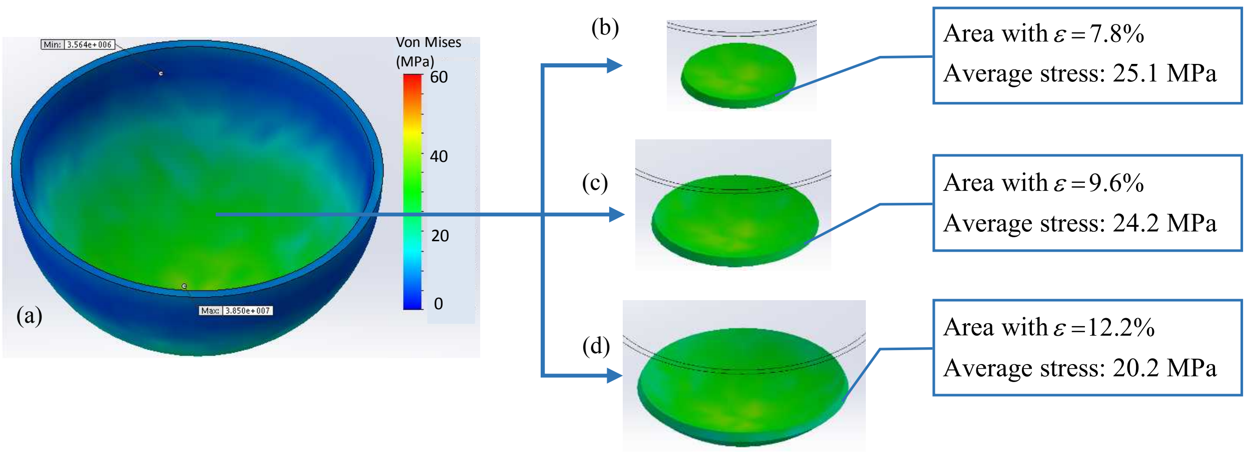

Fig. 25 Stress distribution in large-size product and stress values around area of ε =10%

First, the entire stress distribution of the large-size product is shown in Fig. 25 (a). Obviously, the stress is increasingly higher from top to bottom of the product because it is affected by the surface friction between the product and mold die and by the change of force components due to the applied force. In the previous report, we found that the suitable stress of forming bamboo fiber plane board should be from 20 to 50 MPa (Ogawa, et al., 2010). Therefore, we examine the average stress in the areas around ε=10%. In Fig. 5 (b) and (c), the average stresses are found out to be suitable, but in Fig. 25(d) the stress is found to be the boundary value.

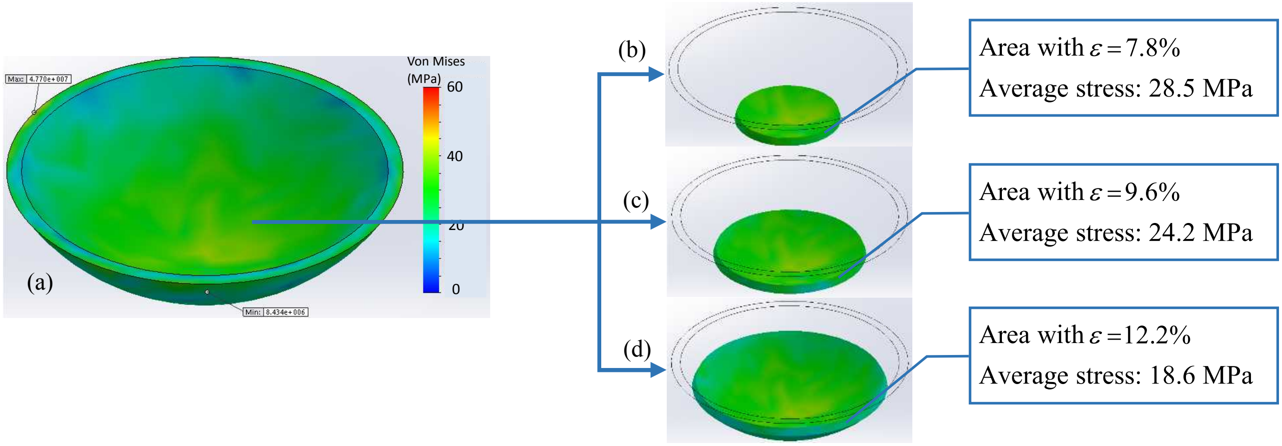

Fig. 26 Stress distribution in medium-size product and stress values around area of $\varepsilon = 10\%$

Second, the entire stress distribution of the medium-size product is shown in Fig. 6 (a). Generally, we also can see that stress is increasingly higher from top to bottom of the product. Similar to the case of ε large-size product, we found that average stress of areas with ε = 7.8% and 9.6% which are 28.5 and 24.2 MPa, respectively, in Fig. 6 (b) and (c) are suitable for our hot forming condition which should be from 20 to 50 MPa. In the area with ε = 12.2% in Fig. 6 (d), its average stress is only 18.6 MPa while this area's stress has a critical role in gluing the outer parts of our product as explained in Sec. 3.3. Hence, it can be also seen that the dimensions must be more accurate at the jointing part of the expansion sheet under lower press stress conditions, which is predicted by FEM such as Solidworks Simulation, because there is complex press stress distribution at the complex shape product in the second step press forming process.

Finally, the entire stress distribution of small-size product is shown in Fig. 7 (a). For the area with ε= 8.9%, its average stress with 28.5 MPa is a suitable value for our forming process as we can see our product in Fig. 19 (a). Besides, regarding ε = 10.2% and no cutting in the bamboo fiber sheet, we measured the average stress of its top surface (the donut shape) and it is very high, up to 80.5 MPa, especially in the outer part. However, this is considered the influence of the Hertz contact situation because it is found in quite thin areas.

As a result, it can be seen that high accuracy is required to join the bamboo sheets at the area under a lower press stress than a suitable press stress. The expansion sheet can be designed with the relative volume variation ε considering the press stress distribution.

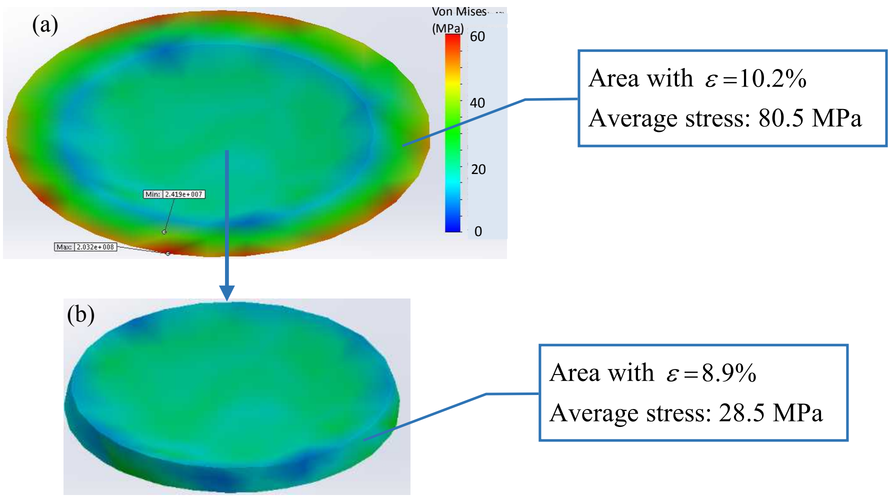

Fig. 27 Stress distribution in small-size product and stress values around area of $\varepsilon = 10\%$

4. Conclusion

In the present report, we discuss a novel fabricating method for the three-dimensional shell shape products made of pure 100% bamboo fibers extracted with a machining center in a sustainable manufacturing system focusing on the natural growth of bamboo. In particular, we propose a novel method of hot press fabricating the hemisphere shell shape as one of the complex shell products. From experimental results, the following conclusions are obtained.

(1) The proposed two-step concept of hot press forming is found to be effective to fabricate the three-dimensional shell shape product made of pure 100% bamboo fibers. With this method, a suitable treatment between first and second step is considered important to assist the liquid flow performance and plastic zone of molding material.

(2) We demonstrate that the relative volume variation ε between the expansion sheets and product shell shape is an essential factor to generate the fine press molding shell product made of pure 100% bamboo fibers at the suitable treatment between the first step and the second step, and find out its criterion value as a suitable treatment between the first and second step. It can also be seen that high accuracy is required for the expansion sheets around the lower press stress area at the second step forming.

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